FEB 14 2000 <i>Sta. 15</i>	ENGINEERING DATA TRANSMITTAL 20	Page 1 of <u>3</u> 1. EDT 627034
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				Validation & Configuration				
				Control				

16. KEY			
Approval Designator (F)	Reason for Transmittal (G)	Disposition (H) & (I)	
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1	1	Design Agent JJ Irwin	<i>JJ Irwin</i>	1-18/2000	R3-86						
1	1	Cog. Eng. FJ Heard	<i>FJ Heard</i>	1/23/99	H0-34						
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1	1	Safety <i>N</i> JR Brehm	<i>JR Brehm</i>	2/3/00	R3-26						
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18. <i>FJ Heard</i> Signature of EDT Originator Date: <u>12/23/99</u>	19. <i>CR Miska</i> Authorized Representative for Receiving Organization Date: <u>2-11-00</u>	20. <i>T Choho</i> Design Authority/Cognizant Manager Date: <u>1/27/00</u>	21. DOE APPROVAL (If required) Ctrl No. _____ ☐ Approved ☐ Approved w/comments ☐ Disapproved w/comments
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EDT-627034 Pg. 2/3

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Pages:	3	Date:	Jan. 6, 2000

Subj: Arrow Verification

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Director of Operations &
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Date: Jan. 6, 2000

Company Name: Applied Flow Technology

Signatory's Position: Director of Operations

Signature: Thomas Glasen

(on behalf of) _____

ARROW (Version 2) - Commercial Software Validation and Configuration Control

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Abstract: ARROW (Version 2), a compressible flow piping network modeling and analysis computer program from Applied Flow Technology, was installed for use at the U.S. Department of Energy Hanford Site near Richland, Washington. A series of sample problems were performed to validate the software and confirm proper installation. The sample problems are compared to published results.

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ARROW (Version 2) – Commercial Software Validation and Configuration Control

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F. J. Heard
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December 1999

ABSTRACT

ARROW (Version 2) a compressible flow piping network modeling and analysis program from Applied Flow Technology was installed for use at the Department of Energy (DOE) Hanford site near Richland, Washington. A series of tests were performed to validate the software and confirm proper installation. The sample problems are compared with published results.

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1.0 INTRODUCTION AND PURPOSE

The purpose of this report is to document the validation of AFT ARROW (Version 2) computer code consistent with the requirements of HNF-PRO-309 (Revision 0) "Computer Software Quality Assurance Requirements" for commercial-off-the-shelf (COTS) software.

AFT ARROW, hereafter referred to as ARROW, was supplied by Applied Flow Technology Corporation in Woodlawn Park, Colorado for use at the Department of Energy's Hanford site near Richland, Washington. "Applied Flow Technology", "AFT", and "AFT ARROW" are registered trademarks of the Applied Flow Technology Corporation.

Software validation is the process of evaluating a system or component during or at the end of the development process to determine whether it satisfies specified requirements. Validation involves running test cases to ensure that the computed output meets specified expectations and requirements, including numerical correctness of the results based on comparisons with alternate calculations (e.g., hand calculations, analytical solutions, or acceptance testing).

2.0 DESCRIPTION AND APPLICATION

ARROW is piping network analysis tool for use with compressible flows. ARROW is intended as an aide for network analyses and not as a replacement for other design and analysis methods, including sound judgement, hand calculations, or independent checks. ARROW is supplied by Applied Flow Technology Corporation in Woodlawn Park, Colorado. "Applied Flow Technology", "AFT", and "AFT ARROW" are registered trademarks of the Applied Flow Technology Corporation.

2.1 Overview

ARROW uses a graphical interface that is based on drag-and-drop operations inherent to most Windows based applications. (Windows is a registered trademark of the Microsoft Corporation.) This allows the user to build a piping network using selections from a palette of components. Date is entered or edited for each of the components by double-clicking the component of interest. Additional global editing features are available from the menu or tool bars that simplify making large-scale changes tot he model.

ARROW has five integrated subordinate windows. The five windows can be viewed as an integrated environment for entering, processing, analyzing, and documenting the results of a piping network simulation. The user will work from one of the five windows at all times. Of the five windows, two are input windows and three are output windows

2.1.1 Input Windows

The two input windows are the Workspace window and the Model Data windows. These two windows, one graphical and the other text-based, process the input data for the model.

2.1.2 Output Windows

The three output windows are the Output, the Graph Results, and the Visual Report. The Output window is text-based. The Graph Results and Visual Report windows are graphical. These three windows are essential for reviewing the results of the analysis, spotting analysis errors, and preparing the results for documentation.

2.2 Modeling Capabilities

ARROW is a compressible steady-state one-dimensional Newtonian fluid network flow analysis program and can be used to model a variety of engineering systems including:

- Open and closed (recirculating) systems
- Network systems that branch or loop, with no limit on the number of loops
- Pressure driven systems
- Compressor or fan driven systems, including multiple compressors or fans in parallel and/or in series

- Compressors or fans with variable speed, controlled discharge pressure and controlled flow
- Systems with pressure and/or flow control valves
- Systems with valves closed and compressors/fans turned off
- Systems with non-ideal gases
- Systems that experience sonic choking, including multiple sonic choke points
- Systems with non-reacting flow stream mixing and user defined mixtures (with optional Chempak)
- Systems with elevations changes or rotation such in turbomachinery

ARROW also provides hundreds of standard loss models based on well known references such as; Crane (1988), Idelchik (1994), and Miller (1990), but also allows the user to enter there own loss data. Variable or dynamic loss coefficients are supported. Variable loss coefficients may depend on flow, area ratios, and/or flow splits (such as tee's and wye's), and the angle of the connecting piping. ARROW also provides automatic calculation of friction factors using the well-known Colebrook-White correlation. Also provided is an extensive database of thermophysical properties for numerous fluids and gases

ARROW uses a Newton-Raphson method to solve the fundamental equations of pipe flow that govern conservation of mass, momentum, and energy. Solutions are obtained by iterative matrix methods that have been optimized for speed and convergence.

2.3 Engineering Assumptions

ARROW is based on the following fundamental fluid mechanics assumptions:

- Compressible flow
- All gases are superheated
- Steady-state conditions
- One-dimensional flow
- No chemical reactions
- Supersonic flow does not exist in the system

3.0 CONFIGURATION CONTROL

ARROW was purchased from Applied Flow Technology located in Woodlawn, Colorado. ARROW is currently licensed for a single user on a single personal computer within a Windows 9x or NT environment. ARROW is considered commercial-off-the-shelf (COTS) software.

3.1 Hardware

ARROW was installed on an AST Bravo with a 200-MHz Pentium processor and 128 MB of main memory. The property tag is WC65744. The operating system is Windows 95 Version 4.00.950B. ARROW was installed by running the automated SETUP program located on the installation disk.

The ARROW installation program is very simple and standard for most Windows based applications. SETUP asks you where to unzip the program and where (i.e., pathname) to install the program. The executable files supplied with ARROW are compiled code. No source code is supplied. SETUP handles all the file manipulations, short cuts, desktop icons, and registry entries required by Windows. ARROW was installed using the following default pathname: C:\ARROW.

To install and run AFT ARROW, the computer must meet the following minimum requirements:

Table 3-1. Hardware and System Requirements

Feature	Required	Recommended
IBM – Compatible Processor	80486	Pentium or higher
Hard Disk Space	15 Mb	
Floppy Drive	3½ -Inch	
Monitor Resolution	VGA	SVGA or higher
Random Access Memory (RAM)	32Mb	48Mb
Mouse	Yes	
Math Co-processor	No	Yes
MS-Windows	Windows 95 or 98	Windows NT

3.2 License Key

A license key is required to activate the AFT ARROW program for use. The license key is supplied by the vendor on a separate floppy disk. The user must supply the license key when requested during setup. The license key is copied from the floppy and stored within a hidden and encrypted file somewhere on the system. ARROW will check for the existence and content of the license file each time the program is activated.

The license key contains information pertaining to the registered purchaser of the program, authorized number of users, and time remaining for the annual software upgrade maintenance (SUM) and help agreement if purchased with ARROW.

3.3 Problem Reporting

AFT ARROW provides an extensive context searchable online help manual and access to additional help, frequently asked questions (FAQ's), and modeling tips via the internet (www.aft.com).

Modeling problems, bug reports, and general pleas for assistance can be supplied to AFT via support (support@aft.com). A bug report is first verified and then acknowledged usually within two to three business days. The response may or may not solve the problem, but may provide a workaround until the problem is fixed. If requested, a special version of ARROW containing the bug fix (when available) can be supplied to the customer. If the error(s) persist, a special version of ARROW containing an extensive set of debugging tools can be supplied for use by the customers in an attempt to resolve the problem.

Users are notified via email when an update to ARROW is available. Minor updates are received several times a year. Major updates are received approximately once a year. Most of the minor revisions address bugs that have been found and corrected. The major once-a-year revisions usually deal with major enhancements and new capabilities that have been added. Whether or not to update depends on the time remaining in the annual SUM agreement, current workscope, and the nature of the bug fixes or enhancements.

3.4 User Manual

The user manual for AFT ARROW is a soft cover booklet running about 250 pages. The user manual is also available via online help. A single copy of the user manual was included with the software and is currently located at 2440 Stevens Center Room 1704. Additional copies can be purchased from Applied Flow Technology.

4.0 VALIDATION

The ARROW user's manual contains a detailed discussion of the fundamental concepts and conventions used in processing piping systems and how to interpret the database information imbedded within ARROW (see Section 2.1). ARROW assumes that the user has a good general understanding of engineering hydraulics. ARROW is designed for use by persons who possess a level of knowledge consistent with that obtained from an undergraduate engineering course in the analysis of piping systems and fluid networks.

4.1 Internal Databases

Most engineering analyses involve processing very large amounts of information, some of which is critical, but most of which is of lesser importance. The key to analyze accurately and efficiently is the proper identification of the critical information. Two databases embedded within ARROW manage information associated with the fluid properties and pressure loss factors.

4.1.1 Fluids

Density and dynamic viscosity are two fluid properties required for all analyses. Fluid vapor pressure is optional. ARROW provides a fluid database for numerous common fluids. If the working fluid is not in the database, the user can enter fluid properties into a custom database for later recall.

Spot checks of the properties for air, helium, hydrogen, oxygen, nitrogen, and water against the values summarized in HOLMAN (1990) showed very good agreement.

4.1.2 Losses

ARROW provides hundreds of standard loss models based on well known references such as; Crane (1988), Idelchik (1994), and Miller (1990), but also allows the user to enter their own loss data. Variable or dynamic loss coefficients are supported. Variable loss coefficients may depend on flow, area ratios, and/or flow splits (such as tee's and wye's), and the angle of the connecting piping. ARROW also provides automatic calculation of friction factors using the well-known Colebrook-White correlation.

Spot checks of representative loss coefficients for valves and fittings against values summarized within Crane (1988) showed very good agreement.

4.2 Test Problems

Twenty-one sample problems (input files) are supplied with ARROW. All twenty-one input files are installed in the VERIFY sub-directory below the C:\ARROW directory. The sample problems model systems that range in size from one pipe to seventy pipes. All of the sample problems are for systems with solutions available in published literature. Sample problem 5 requires the optional Chempak module for modeling mixtures and could not be run.

Table 4-1 lists the sample problems and provides a brief description of each model. Appendix A summarizes the model, the reference, and the output test results. Appendix A contains copyrighted material. This material is printed with permission from Applied Flow Technology Corporation.

Table 4-1. Listing of Sample Problems Supplied with ARROW

Number	Description	File Name
1	1 pipe, 2 junctions Compressible air flow in a pipe.	Verify1.aro
2	1 pipe, 2 junctions Compressible methane flow in a pipe.	Verify2.aro
3	1 pipe, 2 junctions Compressible steam flow in a pipe.	Verify3.aro
4	1 pipe, 2 junctions Compressible air flow in a long pipe.	Verify4.aro
5	1 pipe, 2 junctions Compressible natural gas (mixture) flow in a 100-mile 14-inch pipeline. Requires optional Chempak. Problem.	Verify5.aro
6	1 pipe, 2 junctions Compressible steam flow in a pipe.	Verify6.aro
7	1 pipe, 2 junctions Compressible air flow in a pipe.	Verify7.aro
8	2 pipes, 3 junctions Compressible air flow in a branching network.	Verify8.aro
9	1 pipe, 2 junctions Compressible air flow in a pipe.	Verify9.aro
10	1 pipe, 2 junctions Compressible isothermal flow in a pipe.	Verify10.aro
11	1 pipe, 2 junctions Compressible air flow in a duct.	Verify11.aro
12	1 pipe, 2 junctions Compressible air flow in a convergent nozzle.	Verify12.aro
13	2 pipes, 4 junctions Compressible natural gas flow in a pipe. Maximum length to prevent choked flow.	Verify13.aro
14	1 pipe, 2 junctions Compressible air flow in a pipe. Choked flow rate.	Verify14.aro
15	1 pipes, 2 junctions Compressible air flow in a pipe.	Verify15.aro
16	1 pipes, 2 junctions Compressible air flow in a pipe. Discharge pressure.	Verify16.aro

Number	Description	File Name
17	1 pipes, 2 junctions Compressible air flow in a pipe. Discharge pressure.	Verify17.aro
18	1 pipes, 2 junctions Compressible air flow in a pipe. Discharge pressure.	Verify18.aro
19	1 pipes, 2 junctions Compressible air flow in a pipe. Discharge pressure.	Verify19.aro
20	1 pipes, 2 junctions Compressible air flow in a pipe. Discharge pressure.	Verify20.aro
21	1 pipes, 2 junctions Compressible air flow in a pipe. Discharge pressure.	Verify21.aro

5.0 RESULTS

Twenty-one sample problems were successfully executed and inspected. The input and output files are attached in Appendix A.

5.1 Acceptance Criteria

The following acceptance criteria were used to evaluate the results of the sample runs:

- 1) Each of the sample problems must execute and converge using the default or input supplied convergence criteria.
- 2) Each of the sample problems, with the exception of sample #5, was compared to the published solutions.

5.2 Test Results

The pertinent results from each of the sample problems are summarized within the following tables and discussed within the following paragraphs. Most of the differences in flow rates and head losses were due to a combination of items: tighter tolerances (both global and individual pipes/junctions), friction factor models, and the rigorous treatment of pump heads (fitted polynomial versus linear interpolation). These differences were judged to reflect the improvements associated with the general state of knowledge now available for use within ARROW. These differences should not reflect adversely given the relatively simple hand calculations and techniques that were used to derive the published solutions.

5.2.1 Sample Problem #1

Sample problem # 1 consists of one pipe and two junctions. Sample problem #1 models simple compressible adiabatic flow in a pipe from ANDERSON (1982). Air is the working gas.

The pipe is 30 meters in length with a hydraulic diameter of 0.15 meters. The friction factor is supplied as an explicit f (0.02). The problem states that the inlet mach number is 0.3, the inlet pressure P_1 is 1 atm, and the inlet temperature T_1 is 273 °K. From the Ideal Gas Law: density, sonic speed, and mass flow rate can be calculated. Once the mass flow rate is known, it can be applied as an exit flow demand.

The results for sample problem #1 are presented in Table 5-1. The corresponding results from ANDERSON (1982) are shown. Appendix A contains a detailed description of the sample problem and listings of both the input and output results.

Table 5-1. Comparison of Results for Sample Problem #1

Parameter	Anderson	AFT Arrow 2.0
M_2 – Mach number at exit	0.475	0.4757
P_2 – Static pressure at exit (atm)	0.624	0.6239
T_2 – Static temperature at exit (°K)	265.8	266.0
P_{o2} – Stagnation pressure at exit (atm)	0.728	0.7279

5.2.2 Sample Problem #2

Sample problem # 2 consists of one pipe and two junctions. Sample problem #2 models compressible flow in a pipe from SAAD (1993). Methane is the working gas.

As specified, inlet conditions are known and the outlet conditions are sonic. The pipe length that yields sonic flow is the objective. With the known inlet conditions, an implied mass flow rate exists. To pose the problem in AFT Arrow terms; a few simple calculations are needed to obtain the mass flow rate. Once obtained, it is applied as a flow demand at the exit.

The problem states that the inlet velocity V_1 is 30 m/s, the inlet pressure P_1 is 0.8 MPa, and the inlet temperature T_1 is 320 °K. From the ideal gas law, density, sonic speed and mass flow rate can be determined. Once determine the mass flow rate can be applied as an exit demand. AFT ARROW does not solve for pipe length. Therefore, several manual iterations are required with different pipe lengths to obtain sonic flow ($M = 1$) at the exit.

The results for sample problem #2 are presented in Table 5-2. The corresponding results from SAAD (1993) are shown. Appendix A contains a detailed description of the sample problem and listings of both the input and output results.

Table 5-2. Comparison of Results for Sample Problem #2

Parameter	Saad	AFT Arrow 2.0
Maximum pipe length (m)	4024	4029.49
P_2 – Static pressure at exit (kPa)	48.2	48.10
V_2 – Velocity at exit (m/s)	433.17	433.13
T_2 – Static temperature at exit (°K)	278.43	277.88

5.2.3 Sample Problems #3

Sample problem #3 consists of one pipe and two junctions. Sample problem #3 models 600-psig steam at 850 °F flowing through a system with 400 feet of horizontal 6-inch Schedule 80 pipe at a rate of 90,000 pounds per hour.

The results for sample problem #3 are presented in Table 5-3. Comparison is made to the published results from CRANE (1988). Appendix A contains a detailed description of the sample problem and listings of both the input and output results.

Table 5-3. Comparison of Results for Sample Problem #3

Parameter	Crane	AFT Arrow 2.0
Static pressure drop (psi)	40.1	41.59

5.2.4 Sample Problem #4

Sample problem #4 consists of one pipe and two junctions. Sample Problem #4 models air flowing at 65-psig steam and 110 °F through 75 feet of 1-inch Schedule 40 pipe at a rate of 100 standard cubic feet per minute (scfm).

The results for sample problem #4 are presented in Table 5-4. Comparison is made to the published results from CRANE (1988). Appendix A contains a detailed description of the sample problem and listings of both the input and output results.

Table 5-4. Comparison of Results for Sample Problem #4

Parameter	Crane	AFT Arrow 2.0
Static pressure drop (psi)	2.61	2.712
Volumetric flow rate at inlet (ft ³ /min)	20.2	20.21
Volumetric flow rate at outlet (ft ³ /min)	20.9	20.93
Velocity inlet (ft/min)	3,367	3,368
Velocity inlet (ft/min)	3,483	3,487

5.2.5 Sample Problem #5

Sample Problem 5 could not be run because it requires the optional Chempak module. Table 5-5 was purposely left blank.

The results for sample problem #5, as supplied by Applied Flow Technology, are presented in Appendix A. Comparison is made to the published results from CRANE (1988).

Table 5-5. Comparison of Results for Sample Problem #5

5.2.6 Sample Problem #6

Sample problem #6 consists of one pipe and two junctions. Sample Problem #6 models saturated steam at 170-psia feeding a pulp digester through and 30 feet of 1-inch Schedule 40.

The results for sample problem #6 are presented in Table 5-6. Comparison is made to the published results from CRANE (1988). Appendix A contains a detailed description of the sample problem and listings of both the input and output results.

Table 5-6. Comparison of Results for Sample Problem #6

Parameter	Crane Modified Darcy Formula	Crane Sonic Velocity Formula	AFT Arrow 2.0
Mass flow rate (lbm/hr)	11,780	11,180	11,042
Exit static enthalpy (Btu/lbm)	N/A	1,196	1,147.6
Exit static temperature (°F)	N/A	317	240.7

5.2.7 Sample Problem #7

Sample problem #7 consists of one pipe and two junctions. Air supplied at a pressure of 19.3-psig and a temperature of 100 °F is measured at a point 10 feet from the outlet of ½-inch Schedule 80 pipe discharging to the atmosphere.

The results for sample problem #7 are presented in Table 5-7. Comparison is made to the published results from CRANE (1988). The Crane prediction indicates that this pipe will have subsonic velocity at the exit and hence will not choke. However, a more proper formulation of this problem shows that sonic choking will occur. This is a good example of the limitations of simplified methods such as Crane. The discrepancy comes from how to handle the exit loss of the air as it discharges to atmosphere. The Crane solution takes the appropriate K factor, equal to 1, and lumps it together with the pipe friction to obtain an overall K factor of 7.04. However, if the K factor is applied at the discharge tank and not averaged along the pipe, the flow chokes. The predicted choked flow rate is 64.3 scfm. This is not drastically different from Crane's prediction, and well within typical engineering uncertainty. However, the difference, which is small here, could be larger in other applications.

Appendix A contains a detailed description of the sample problem and listings of both the input and output results.

Table 5-7. Comparison of Results for Sample Problem #7

Parameter	Crane	AFT Arrow 2.0
Mass flow rate (scfm)	62.7	63.3

5.2.8 Sample Problem #8

Sample problem #8 consists of two pipes and three junctions. Sample problem #8 represents a branching system where the two pipe lengths necessary to obtain a measured pressure and choked flow are unknown. Air is the working gas.

ARROW does not solve for pipe length. However, the length of Pipe #1 can be manually changed to obtain the measured pressure. The resulting mass flow rate is then used as input for Pipe #2.

The results are presented in Table 5-8. Comparison is made to the published results from FOX (1985). The results agree very closely. Appendix A contains a detailed description of the sample problem and listings of both the input and output results.

Table 5-8. Comparison of Results of Sample Problem #8

Parameter	Fox & McDonald	AFT Arrow 2.0
L_{1-3} - length to choking (m)	4.99	4.994
V_1 - Velocity at point 1 (m/s)	65.3	65.2
T_1 - Temperature at point 1 (°K)	294	293.9
M_1 - Mach number at point 1	0.19	0.19
M_2 - Mach number at point 2	0.40	0.40
P_2 - Pressure at point 2 (mm Hg gauge)	-18.9	-18.86*
L_{1-2} - length to measured pressure (m)	4.29	4.29*

* AFT Arrow does not have the ability to solve for pipe length, so the length was manually input. With this known length, the AFT Arrow Mach number at M_2 should agree with Fox & McDonald's, and it does. The resulting mass flow rate is then used as input for AFT Arrow pipe #2.

5.2.9 Sample Problem #9

Sample problem #9 consists of one pipe and two junctions. As specified, inlet conditions are known and outlet conditions need to be determined. With the known inlet conditions, an implied mass flow rate exists. To pose the problem in AFT Arrow terms a few simple calculations are needed to obtain the mass flow rate. Once obtained, it is applied as a flow demand at the exit.

The results are presented in Table 5-9. Comparison is made to the published results from LINDEBURG (1984). Appendix A contains a detailed description of the sample problem and listings of both the input and output results.

Table 5-9. Comparison of Results of Sample Problem #9

Parameter	Lindeburg	AFT Arrow 2.0
M_2 – Mach number at exit	0.35	0.356
P_2 – Pressure at exit (psia)	10.26	10.09

5.2.10 Sample Problem #10

Sample problem #10 consists of one pipe and two junctions. Methane is the working gas. The problem states that the pipe length is 75 miles and 40 inches in diameter with an explicit friction factor of 0.00936. The inlet pressure P_1 is 650-psia. The outlet pressure P_2 is 450-psia. Determine the mass flow rate.

The results are presented in Table 5-10. Comparison is made to the published results from LINDEBURG (1984). Appendix A contains a detailed description of the sample problem and listings of both the input and output results.

Table 5-10. Comparison of Results for Sample Problem #10

Parameter	Lindeburg	AFT Arrow 2.0
Mass flow rate (lbm/s)	456	478

5.2.11 Sample Problem #11

Sample problem #11 consists of one pipe and two junctions. Air is the working gas.

Exit conditions are known. The inlet conditions need to be determined for the specified volumetric flow. With the known exit conditions, a few simple calculations are needed to obtain the implied mass flow rate. Once obtained, it is applied as an inlet flow demand.

In AFT Arrow, the discharge pressure can be specified. The temperature can be specified at the exit junction, but the actual discharge is what is displayed for the pipe exit. The pipe exit

temperature depends on the inlet temperature and the thermodynamic process in the pipe, which is adiabatic. Therefore, to solve this problem the inlet static temperature at J1 must be guessed until the pipe delivers 293 K at the exit.

The results are presented in Table 5-11. Comparison is made to the published results from SAAD (1993). Appendix A contains a detailed description of the sample problem and listings of both the input and output results.

Table 5-11. Comparison of Results for Sample Problem #11

Parameter	Saad	AFT Arrow 2.0
M_2 – Mach number at exit	0.685	0.689
M_1 – Mach number at inlet	0.347	0.347
P_1 – Static pressure at inlet (kPa)	306	308.1
T_1 – Static temperature at inlet (°K)	312.76	312.9

5.2.12 Sample Problem #12

Sample problem #12 consists of one pipe and two junctions. Air is the working gas. Inlet conditions are known. Air flows isentropically through a convergent nozzle which feeds an insulated constant area duct.

The results are presented in Table 5-12. Comparison is made to the published results from SAAD (1993). Appendix A contains a detailed description of the sample problem and listings of both the input and output results.

Table 5-12. Comparison of Results for Sample Problem #12

Parameter	Saad	AFT Arrow 2.0
Mass flow rate when choked (kg/s)	2.11	2.10
M_1 – Mach number at inlet	0.603	0.604
P_1 – Static pressure at inlet (MPa)	2.106	2.114
T_1 – Static temperature at inlet (°K)	427.8	429.6
$P_{2,choke}$ – Static back pressure for choking (MPa)	1.203	1.217

5.2.13 Sample Problem #13

Sample problem #13 consists of two pipes and four junctions. Natural gas is the working gas. Inlet conditions are known. Outlet conditions are to be determined. With the known inlet conditions, a few simple calculations are needed to obtain the implied mass flow rate. Once obtained, it is applied as an outlet flow demand.

The first pipe represents the pipe from point 1 to 2. The second pipe represents the pipe from point 1 to the choking point. AFT Arrow does not explicitly solve for pipe length. To obtain the maximum pipe length, different lengths must be guessed with lengths that exceed sonic flow discarded.

The results are presented in Table 5-13. Comparison is made to the published results from SAAD (1993). All results agree closely. The AFT Arrow static pressure below which choking occurs is the pipe exit static pressure. Appendix A contains a detailed description of the sample problem and listings of both the input and output results.

Table 5-13. Comparison of Results for Sample Problem #13

Parameter	Saad	AFT Arrow 2.0
P_2 – Static pressure at exit (kPa)	263.16	262.0
M_2 – Mach number at exit	0.38	0.3818
L_{1-2} – Length to reach 500 kPa (m)	544.79	558.5
L_{T^*} – Length to reach sonic choke point (m)	710	709.8
P_{T^*} – Static pressure choke point (kPa)	114.46	114.9
M_{T^*} – Mach number at isothermal choke point	0.874	0.8704

5.2.14 Sample Problem #14

Sample problem #14 consists of one pipe and two junctions. The objective is to solve for the choked flow rate. Air is the working gas.

The results are presented in Table 5-14. Comparison is made to the published results from PERRY. Appendix A contains a detailed description of the sample problem and listings of both the input and output results.

Table 5-14. Comparison of Results for Sample Problem #14

Parameter	Perry	AFT Arrow 2.0
Mass flow rate (kg/s)	2.7	2.716

5.2.15 Sample Problem #15

Sample problem #15 consists of one pipe and two junctions. Air is the working gas. Inlet conditions are known. Outlet conditions need to be determined. With the known inlet conditions, a few simple calculations are needed to obtain the implied mass flow rate. Once obtained, it is applied as an outlet flow demand.

The results are presented in Table 5-15. Comparison is made to the published results from JANNA (1983). Appendix A contains a detailed description of the sample problem and listings of both the input and output results.

Table 5-15. Comparison of Results for Sample problem #15

Parameter	Janna	AFT Arrow 2.0
M_2 – Mach number at exit	0.14	0.1355
P_2 – Pressure at exit (psia)	9.63	9.836
T_2 – Temperature at exit (°R)	528.8	528.9

5.2.16 Sample Problem #16

Sample problem #16 consists of one pipe and two junctions. Air is discharged from a high-pressure tank through a 4-inch (Schedule 40) vent line into the atmosphere. The mass flow is given as 72,000 lbm/hr. Stagnation conditions within the tank are $P_o = 600$ -psig (constant) and $T_o = 120$ °F. The equivalent length of the pipe is 90 feet.

The results are presented in Table 5-16. Comparison is made to the published results from NAYYAR (1992). Appendix A contains a detailed description of the sample problem and listings of both the input and output results.

Table 5-16. Comparison of Results for Sample Problem #16

Parameter	Nayyar	AFT Arrow 2.0
M_1 – Mach number at valve	0.317	0.318
P_1 – Pressure at valve (psia)	128.46	128.66

5.2.17 Sample Problem #17

Sample problem #17 is identical to sample problem #16, except that the mass flow rate is doubled.

The results are presented in Table 5-17. Comparison is made to the published results from SAAD (1992). Appendix A contains a detailed description of the sample problem and listings of both the input and output results.

Table 5-17. Comparison of Results for Sample Problem #17

Parameter	Nayyar	AFT Arrow 2.0
M_1 – Mach number at valve	0.317	0.318
P_1 – Pressure at valve (psia)	256.93	257.32

5.2.18 Sample Problem #18

Sample problem #18 is identical to sample problem #16, except that the pipe length is doubled.

The results are presented in Table 5-18. Comparison is made to the published results from SAAD (1992). Appendix A contains a detailed description of the sample problem and listings of both the input and output results.

Table 5-18. Comparison of Results for Sample Problem #18

Parameter	Nayyar	AFT Arrow 2.0
M_1 – Mach number at valve	0.243	0.243
P_1 – Pressure at valve (psia)	168.52	168.69

5.2.19 Sample Problem #19

Sample problem #19 is identical to sample problem #16, except that the air temperature is 500 °F.

The results are presented in Table 5-19. Comparison is made to the published results from SAAD (1992). Appendix A contains a detailed description of the sample problem and listings of both the input and output results.

Table 5-19. Comparison of results for Sample Problem #19

Parameter	Nayyar	AFT Arrow 2.0
P_1 – Pressure at valve (psia)	165.29	165.60

5.2.20 Sample Problem #20

Sample problem #20 is identical to sample problem #16, except that the pipe diameter has been decreased to 2-inches.

The results are presented in Table 5-20. Comparison is made to the published results from SAAD (1992). Appendix A contains a detailed description of the sample problem and listings of both the input and output results.

Table 5-20. Comparison of Results for Sample problem #20

Parameter	Nayyar	AFT Arrow 2.0
M_1 – Mach number at valve	0.235	0.235
P_1 – Pressure at valve (psia)	661.96	662.56

5.2.21 Sample Problem #21

Sample problem #21 is identical to sample problem #16, except that the pipe diameter has been increased to 8-inches.

The results are presented in Table 5-21. Comparison is made to the published results from SAAD (1992). Appendix A contains a detailed description of the sample problem and listings of both the input and output results.

Table 5-21. Comparison of Results for Sample Problem #21

Parameter	Nayyar	AFT Arrow 2.0
M_1 – Mach number at valve	0.4096	0.4142
P_1 – Pressure at valve (psia)	25.15	24.95

6.0 SUMMARY AND CONCLUSIONS

The ARROW (Version 2) compressible flow network analysis program has been installed and successfully validated for use. Based on a direct comparison of twenty of twenty-one sample problems to published results, the ARROW computer program is judged acceptable for use at the Hanford site. Furthermore, the use of an encrypted license key to assures proper installation and configuration control

The pertinent results from each of the sample problems have been summarized within the preceding tables. It must be noted that in most cases very good agreement was found. However, a few cases of significant differences between ARROW and the published results were found. Most of the differences in flow rates and pressures were due to a combination of items: tighter tolerances (both global and individual pipes/junctions), friction factor models, and the rigorous treatment component losses

These differences were judged to reflect the improvements associated with the general state of knowledge now automated and available for use within ARROW. These differences should not reflect adversely given the relatively simple hand calculations and techniques that were used to derive the published solutions.

7.0 REFERENCES

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APPENDIX A – SAMPLE PROBLEM DESCRIPTIONS, INPUT, AND OUTPUT

Appendix A contains copyright material. Problem descriptions were printed with permission from Applied Flow Technology Corporation.

TITLE: VERIFY1.ARO

REFERENCE: John D. Anderson, Modern Compressible Flow, 1982, McGraw-Hill, page 76, example 3.4

GAS: Air

ASSUMPTIONS: 1) Adiabatic, 2) Perfect gas

RESULTS:

Parameter	Anderson	AFT Arrow 2.0
M_2 - Mach number at exit	0.475	0.4757
P_2 - Static pressure at exit (atm)	0.624	0.6239
T_2 - Static temperature at exit (deg. K)	265.8	266.0
P_{o2} - Stagnation pressure at exit (atm)	0.728	0.7279

DISCUSSION:

As specified, inlet conditions are known and outlet conditions need to be determined. With the known inlet conditions, an implied mass flow rate exists. To pose the problem in AFT Arrow terms, a few simple calculations are needed to obtain the mass flow rate. Once obtained, it is applied as a flow demand at the exit.

The problem states that the inlet Mach number is 0.3, $P_1 = 1$ atm, $T_1 = 273$ K. From the ideal gas law, density, sonic speed and mass flow rate are:

$$\rho_1 = \frac{P_1}{RT_1} = \frac{1 \text{ atm}}{\left(0.2868 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}\right)(273 \text{ K})} = 1.293 \text{ kg/m}^3$$

$$a_1 = \sqrt{\gamma RT_1} = \sqrt{1.4 \left(287 \frac{\text{J}}{\text{kg} \cdot \text{K}}\right) 273 \text{ K}} = 331.2 \text{ m/s (sonic velocity)}$$

$$\dot{m} = \rho_1 V_1 A = \rho_1 (M_1 a_1) A = \left(1.293 \frac{\text{kg}}{\text{m}^3}\right)(0.3) \left(331.2 \frac{\text{m}}{\text{s}}\right) \left(\frac{\pi}{4} 0.15^2 \text{ m}^2\right) = 2.27 \text{ kg/s}$$

Note that the friction factor in Anderson is the Fanning friction factor. To obtain the Darcy-Weisbach friction factor used in AFT Arrow, multiply the Fanning friction factor by 4.

AFT Arrow 2.0 Input
Numatec Hanford Corporation

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Verify1.aro - Modern Compressible Flow, Example 3.4, pg 76

John D. Anderson
Modern Compressible Flow, 1982, McGraw-Hill
page 76, example 3.4
Air flow in a pipe - Example assumes adiabatic flow and air is a perfect gas

See Verify1.doc MS Word file for comparison with published results

Title: Verify1.aro - Modern Compressible Flow, Example 3.4, pg 76

Number Of Pipes= 1
Number Of Junctions= 2

Length March Solution Method with Mach Number Limits
Segments Per Pipe= 2
Mach Number Increment= .01
Pressure Tolerance= .0001 relative change
Mass Flow Rate Tolerance= .0001 relative change
Enthalpy Tolerance= .0001 relative change
Concentration Tolerance= .0001 relative change
Flow Relaxation= (Automatic)
Pressure Relaxation= (Automatic)

Fluid Database: AFT Standard
Fluid= Air
Max Fluid Temperature Data= 1000 deg. K
Min Fluid Temperature Data= 200 deg. K
Molecular Weight= 28.97 amu
Gas Constant= 0.2868 kJ/kg-K
Critical Pressure= 37.25 atm
Critical Temperature= 132.41 deg. K
Acentric Factor= .021
Equation of State= Ideal Gas
Enthalpy Model= Reference
Specific Heat Ratio Accuracy= High
Atmospheric Pressure= 1 atm
Gravitational Acceleration= 1 g's
Standard Pressure= 14.696 psia
Standard Temperature= 60 deg. F
Turbulent Flow Above Reynolds Number= 4000
Laminar Flow Below Reynolds Number= 2300
Specific Heat Ratio Accuracy= High
Atmospheric Pressure= 1 atm
Gravitational Acceleration= 1 g
Standard Pressure= 14.696 psia
Standard Temperature= 60 deg. F
Turbulent Flow Above Reynolds Number= 4000
Laminar Flow Below Reynolds Number= 2300

Pipe Input Table

Pipe	Name	Pipe Defined	Length	Length Units	Hydraulic Diameter	Hydraulic Diam. Units	Roughness	Roughness Units	Losses (K)	Initial Flow
1	Pipe	Yes	30	meters	0.15	meters	0.02	Explicit f	0	

Pipe	Initial Flow Units	Junctions (Up,Down)	Geometry	Material	Size	Type	Special Condition
1		1, 2	Cylindrical Pipe	Unspecified			None

Assigned Flow Table

AFT Arrow 2.0 Input
Numatec Hanford Corporation

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Verify1.aro - Modern Compressible Flow, Example 3.4, pg 76

Assigned Flow	Name	Object Defined	Database Source	Special Condition	Fluid	Type	Flow	Flow Units	Temperature	Temperature Units
2	Assigned Flow	Yes		None	Air	Outflow	2.27	kg/sec	273	deg. K

Assigned Flow	Loss Model
2	0

Assigned Pressure Table

Assigned Pressure	Name	Object Defined	Database Source	Special Condition	Fluid	Pressure	Pressure Units	Temperature
1	Assigned Pressure	Yes		N/A	Air	1	atm	273

Assigned Pressure	Temperature Units	Loss Factor
1	deg. K	0

AFT Arrow 2.0 Output
Numatec Hanford Corporation

(1)

12/7/99

Verify1.aro - Modern Compressible Flow, Example 3.4, pg 76

John D. Anderson
Modern Compressible Flow, 1982, McGraw-Hill
page 76, example 3.4
Air flow in a pipe - Example assumes adiabatic flow and air is a perfect gas

See Verify1.doc MS Word file for comparison with published results

Title: Verify1.aro - Modern Compressible Flow, Example 3.4, pg 76
Analysis run on: 12/7/99 10:11:29 AM
Input File: C:\AFT Products\AFT Arrow\Verification\verify1.aro

Execution Time= 0.27 seconds
Total Number Of Pressure Iterations= 0
Total Number Of Flow Iterations= 2
Total Number Of Enthalpy Iterations= 2
Number Of Pipes= 1
Number Of Junctions= 2

Length March Solution Method with Mach Number Limits
Segments Per Pipe= 2
Mach Number Increment= .01
Pressure Tolerance= .0001 relative change
Mass Flow Rate Tolerance= .0001 relative change
Enthalpy Tolerance= .0001 relative change
Flow Relaxation= (Automatic)
Pressure Relaxation= (Automatic)

Fluid Database: AFT Standard
Fluid= Air
Max Fluid Temperature Data= 1000 deg. K
Min Fluid Temperature Data= 200 deg. K
Molecular Weight= 28.97 amu
Gas Constant= 0.2868 kJ/kg-K
Critical Pressure= 37.25 atm
Critical Temperature= 132.41 deg. K
Acentric Factor= .021
Equation of State= Ideal Gas
Enthalpy Model= Reference
Specific Heat Ratio Accuracy= High
Atmospheric Pressure= 1 atm
Gravitational Acceleration= 1 g's
Standard Pressure= 14.696 psia
Standard Temperature= 60 deg. F
Turbulent Flow Above Reynolds Number= 4000
Laminar Flow Below Reynolds Number= 2300
Specific Heat Ratio Accuracy= High
Atmospheric Pressure= 1 atm
Gravitational Acceleration= 1 g
Standard Pressure= 14.696 psia
Standard Temperature= 60 deg. F
Turbulent Flow Above Reynolds Number= 4000
Laminar Flow Below Reynolds Number= 2300
Overall Delta Pressure = -0.03409 MPa
Total Inflow= 2.270 kg/sec
Total Outflow= 2.270 kg/sec
Total Energy Inflow= 992.7 kW
Total Energy Outflow= 992.7 kW
Total Heat Transferred Into System= 0.000 kW

Maximum Pressure is 0.1013 MPa at Junction 1 Inlet
Minimum Pressure is 0.06322 MPa at Junction 2 Inlet
Maximum Static Temperature is 4.703 deg. C at Junction 2 Inlet
Minimum Static Temperature is 4.699 deg. C at Junction 1 Inlet

Pipe Output Table

AFT Arrow 2.0 Output
Numatec Hanford Corporation

(2)

12/7/99

Verify1.aro - Modern Compressible Flow, Example 3.4, pg 76

Pipe	Mach # Out	P Static Out (atm)	P Stag. Out (atm)	T Stag. Out (deg. K)	T Static Out (deg. K)	P Stag. In (atm)	Mass Flow (kg/sec)	Rho Static In (kg/m3)	Vel. In (meters/sec)	Vel. Sonic In (meters/sec)
1	0.4757	0.6239	0.7279	277.9	266.0	1.064	2.270	1.293	99.33	330.4

All Junction Table

Jct	P Stag. In (atm)	P Static In (atm)	T Static In (deg. K)	T Stag. In (deg. K)
1	1.0644	1.0000	273.0	277.8
2	0.7279	0.6239	266.0	277.9

TITLE: VERIFY2.ARO

REFERENCE: Michel A. Saad, Compressible Fluid Flow, 2nd Edition, Prentice-Hall, Englewood Cliffs, NJ, 1993, Page 215, example 5.3

GAS: Methane

ASSUMPTIONS: 1) Adiabatic, 2) Perfect gas

RESULTS:

Parameter	Saad	AFT Arrow 2.0
Maximum pipe length (m)	4024	4029.49
P_2 – Static pressure at exit (kPa)	48.2	48.10
V_2 – Velocity at exit (m/s)	433.17	433.13
T_2 – Static temperature at exit (deg. K)	278.43	277.88

DISCUSSION:

As specified, inlet conditions are known and the outlet conditions are sonic. The pipe length that yields sonic flow is the objective. With the known inlet conditions, an implied mass flow rate exists. To pose the problem in AFT Arrow terms, a few simple calculations are needed to obtain the mass flow rate. Once obtained, it is applied as a flow demand at the exit.

The problem states that the inlet velocity V_1 is 30 m/s, $P_1 = 0.8$ MPa, $T_1 = 320$ K. From the ideal gas law, density, sonic speed and mass flow rate are:

$$\rho_1 = \frac{P_1}{RT_1} = \frac{0.8 \text{ MPa}}{\left(0.5179 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}\right)(320 \text{ K})} = 4.823 \text{ kg/m}^3$$

$$\dot{m} = \rho_1 V_1 A = \left(4.823 \frac{\text{kg}}{\text{m}^3}\right) \left(30 \frac{\text{m}}{\text{s}}\right) \left(\frac{\pi}{4} 0.3^2 \text{ m}^2\right) = 10.2265 \text{ kg/s}$$

AFT Arrow does not solve for pipe length. To obtain the maximum pipe length, different lengths must be guessed with lengths that exceed sonic flow discarded.

Note that the friction factor in Saad is the Fanning friction factor. To obtain the Darcy-Weisbach friction factor used in AFT Arrow, multiply the Fanning friction factor by 4.

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AFT Arrow 2.0 Input
Numatec Hanford Corporation

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12/7/99 10:13 AM

Verify2.aro - Methane Example from Saad pp. 215-216

Michel A. Saad
Compressible Fluid Flow, 2nd Edition, Prentice-Hall, Englewood Cliffs, NJ, 1993
page 215, example 5.3
Methane flow - Example assumes methane is a perfect gas and flow is adiabatic

See Verify2.doc MS Word file for comparison with published results

Title: Verify2.aro - Methane Example from Saad pp. 215-216

Number Of Pipes= 1
Number Of Junctions= 2

Length March Solution Method with Mach Number Limits
Segments Per Pipe= 50
Mach Number Increment= .01
Pressure Tolerance= .0001 relative change
Mass Flow Rate Tolerance= .0001 relative change
Enthalpy Tolerance= .0001 relative change
Concentration Tolerance= .0001 relative change
Flow Relaxation= (Automatic)
Pressure Relaxation= (Automatic)

Fluid Database: AFT Standard
Fluid= Methane
Max Fluid Temperature Data= 400 deg. K
Min Fluid Temperature Data= 150 deg. K
Molecular Weight= 16.043 amu
Gas Constant= 0.51790380 kJ/kg-K
Critical Pressure= 4.5988 MPa
Critical Temperature= 190.555 deg. K
Acentric Factor= .008
Equation of State= Ideal Gas
Enthalpy Model= Reference
Specific Heat Ratio Accuracy= High
Atmospheric Pressure= 1 atm
Gravitational Acceleration= 1 g's
Standard Pressure= 14.696 psia
Standard Temperature= 60 deg. F
Turbulent Flow Above Reynolds Number= 4000
Laminar Flow Below Reynolds Number= 2300
Specific Heat Ratio Accuracy= High
Atmospheric Pressure= 1 atm
Gravitational Acceleration= 1 g
Standard Pressure= 14.696 psia
Standard Temperature= 60 deg. F
Turbulent Flow Above Reynolds Number= 4000
Laminar Flow Below Reynolds Number= 2300

Pipe Input Table

Pipe	Name	Pipe Defined	Length	Length Units	Hydraulic Diameter	Hydraulic Diam. Units	Roughness	Roughness Units	Losses (K)	Initial Flow
1	Pipe	Yes	4029.49	meters	0.3	meters	0.00015	Eps/D	0	

Pipe	Initial Flow Units	Junctions (Up,Down)	Geometry	Material	Size	Type	Special Condition
1		1, 2	Cylindrical Pipe	Unspecified			None

Assigned Flow Table

AFT Arrow 2.0 Input
Numatec Hanford Corporation

(2)

12/7/99 10:13 AM

Verify2.aro - Methane Example from Saad pp. 215-216

Assigned Flow	Name	Object Defined	Database Source	Special Condition	Fluid	Type	Flow	Flow Units	Temperature
2	Assigned Flow	Yes		None	Methane	Outflow	10.2265	kg/sec	320

Assigned Flow	Temperature Units	Loss Model
2	deg. K	0

Assigned Pressure Table

Assigned Pressure	Name	Object Defined	Database Source	Special Condition	Fluid	Pressure	Pressure Units	Temperature
1	Assigned Pressure	Yes		N/A	Methane	0.8	MPa	320

Assigned Pressure	Temperature Units	Loss Factor
1	deg. K	0

AFT Arrow 2.0 Output
Numatec Hanford Corporation

(1)

12/7/99

Verify2.aro - Methane Example from Saad pp. 215-216

Michel A. Saad
Compressible Fluid Flow, 2nd Edition, Prentice-Hall, Englewood Cliffs, NJ, 1993
page 215, example 5.3
Methane flow - Example assumes methane is a perfect gas and flow is adiabatic

See Verify2.doc MS Word file for comparison with published results

Title: Verify2.aro - Methane Example from Saad pp. 215-216
Analysis run on: 12/7/99 10:13:19 AM
Input File: C:\AFT Products\AFT Arrow\Verification\verify2.aro

Execution Time= 0.83 seconds
Total Number Of Pressure Iterations= 0
Total Number Of Flow Iterations= 2
Total Number Of Enthalpy Iterations= 2
Number Of Pipes= 1
Number Of Junctions= 2

Length March Solution Method with Mach Number Limits
Segments Per Pipe= 50
Mach Number Increment= .01
Pressure Tolerance= .0001 relative change
Mass Flow Rate Tolerance= .0001 relative change
Enthalpy Tolerance= .0001 relative change
Flow Relaxation= (Automatic)
Pressure Relaxation= (Automatic)

Fluid Database: AFT Standard
Fluid= Methane
Max Fluid Temperature Data= 400 deg. K
Min Fluid Temperature Data= 150 deg. K
Molecular Weight= 16.043 amu
Gas Constant= 0.51790380 kJ/kg-K
Critical Pressure= 4.5988 MPa
Critical Temperature= 190.555 deg. K
Acentric Factor= .008
Equation of State= Ideal Gas
Enthalpy Model= Reference
Specific Heat Ratio Accuracy= High
Atmospheric Pressure= 1 atm
Gravitational Acceleration= 1 g's
Standard Pressure= 14.696 psia
Standard Temperature= 60 deg. F
Turbulent Flow Above Reynolds Number= 4000
Laminar Flow Below Reynolds Number= 2300
Specific Heat Ratio Accuracy= High
Atmospheric Pressure= 1 atm
Gravitational Acceleration= 1 g
Standard Pressure= 14.696 psia
Standard Temperature= 60 deg. F
Turbulent Flow Above Reynolds Number= 4000
Laminar Flow Below Reynolds Number= 2300
Overall Delta Pressure = -0.71410561 MPa
Total Inflow= 10.226500 kg/sec
Total Outflow= 10.226500 kg/sec
Total Energy Inflow= 10,536.053 kW
Total Energy Outflow= 10,536.053 kW
Total Heat Transferred Into System= 0.0000000 kW

Maximum Pressure is 0.80000001 MPa at Junction 1 Inlet
Minimum Pressure is 0.048102446 MPa at Junction 2 Inlet
Maximum Static Temperature is 48.621952 deg. C at Junction 2 Inlet
Minimum Static Temperature is 47.045990 deg. C at Junction 1 Inlet

Pipe Output Table

AFT Arrow 2.0 Output
Numatec Hanford Corporation

(2)

12/7/99

Verify2.aro - Methane Example from Saad pp. 215-216

Pipe	Length (meters)	Mass Flow (kg/sec)	Vel. In (meters/sec)	Vel. Out (meters/sec)	Mach # In	Mach # Out	P Static In (kPa)	P Static Out (kPa)	T Static In (deg. K)
1	4029.4900	10.226500	29.991524	433.13260	0.064798974	0.99336141	800.00006	48.102448	320.00003

Pipe	T Static Out (deg. K)
1	277.87515

All Junction Table

Jct	P Static In (kPa)	P Static Out (kPa)	T Static In (deg. K)	T Static Out (deg. F)
1	800.000061	800.000061	320.00000	116.330002
2	48.102448	48.102448	277.87512	40.505234

TITLE: VERIFY3.ARO

REFERENCE: Crane Co., Flow of Fluids Through Valves, Fittings, and Pipe, Technical Paper No. 410, Crane Co., Joliet, IL, 1988, Page 4-6, example 4-10

GAS: Steam

ASSUMPTIONS: Example does not specify the heat transfer conditions, so it was assumed adiabatic in this model.

RESULTS:

Parameter	Crane	AFT Arrow 2.0
Static pressure drop (psi)	40.1	41.59

DISCUSSION:

Crane does not make a distinction between static and stagnation pressure, and it appears that static pressure is usually assumed. Therefore, the inlet pressure of 600 psig was assumed to be static pressure.

To make a one-to-one comparison, the K factors and friction factor used in Crane was used directly in AFT Arrow. The K factors were modeled as Additional Losses, which evenly spreads the effect of resistance across the entire pipe. In practice, the velocity changes in the pipe can yield different answers for fitting pressure losses depending on where they are actually located.

The AFT Arrow model uses the Redlich-Kwong real gas equation of state for steam. Note that the Crane formula underpredicts the pressure drop (by about 4%), which in most applications is not conservative.

AFT Arrow 2.0 Input
Numatec Hanford Corporation

(1)

12/7/99 10:08 AM

Verify3.aro - Steam flow in a pipe, Example 4-10 from Crane page 4-6

Crane Co.

Flow of Fluids Through Valves, Fittings, and Pipe, Technical Paper No. 410, Crane Co., Joliet, IL, 1988

Page 4-6, example 4-10

Steam flow - Example does not specify the heat transfer conditions, so it was assumed adiabatic in this model

See Verify3.doc MS Word file for comparison with published results

Title: Verify3.aro - Steam flow in a pipe, Example 4-10 from Crane page 4-6

Number Of Pipes= 1

Number Of Junctions= 2

Length March Solution Method with Mach Number Limits

Segments Per Pipe= 10

Mach Number Increment= .01

Pressure Tolerance= .0001 relative change

Mass Flow Rate Tolerance= .0001 relative change

Enthalpy Tolerance= .0001 relative change

Flow Relaxation= .5

Pressure Relaxation= .5

Fluid Database: AFT Standard

Fluid= Steam (Simplified)

Max Fluid Temperature Data= 1500 deg. F

Min Fluid Temperature Data= 200 deg. F

Molecular Weight= 18.016 amu

Gas Constant= 0.1102 Btu/lbm-R

Critical Pressure= 3208.22 psia

Critical Temperature= 1165.09 deg. R

Acentric Factor= .344

Equation of State= Redlich-Kwong

Enthalpy Model= Generalized

Specific Heat Ratio Accuracy= High

Atmospheric Pressure= 1 atm

Gravitational Acceleration= 1 g's

Standard Pressure= 14.696 psia

Standard Temperature= 60 deg. F

Turbulent Flow Above Reynolds Number= 4000

Laminar Flow Below Reynolds Number= 2300

Specific Heat Ratio Accuracy= High

Atmospheric Pressure= 1 atm

Gravitational Acceleration= 1 g

Standard Pressure= 14.696 psia

Standard Temperature= 60 deg. F

Turbulent Flow Above Reynolds Number= 4000

Laminar Flow Below Reynolds Number= 2300

Pipe Input Table

Pipe	Name	Pipe Defined	Length	Length Units	Hydraulic Diameter	Hydraulic Diam. Units	Roughness	Roughness Units	Losses (K)	Initial Flow
1	Pipe	Yes	400	feet	5.761	inches	0.015	Explicit f	3.5	

Pipe	Initial Flow Units	Junctions (Up,Down)	Geometry	Material	Size	Type	Special Condition
1		1, 2	Cylindrical Pipe	Steel	6 inch	schedule 80	None

Assigned Flow Table

AFT Arrow 2.0 Input
Numatec Hanford Corporation

(2)

12/7/99 10:08 AM

Verify3.aro - Steam flow in a pipe, Example 4-10 from Crane page 4-6

Assigned Flow	Name	Object Defined	Database Source	Special Condition	Fluid	Type	Flow	Flow Units	Temperature
2	Assigned Flow	Yes		None	Steam (Simplified)	Outflow	90000	lbm/hr	850

Assigned Flow	Temperature Units	Loss Model
2	deg. F	0

Assigned Pressure Table

Assigned Pressure	Name	Object Defined	Database Source	Special Condition	Fluid	Pressure	Pressure Units	Temperature
1	Assigned Pressure	Yes		N/A	Steam (Simplified)	600	psig	850

Assigned Pressure	Temperature Units	Loss Factor
1	deg. F	0

AFT Arrow 2.0 Output
Numatec Hanford Corporation

(1)

12/7/99

Verify3.aro - Steam flow in a pipe, Example 4-10 from Crane page 4-6

Crane Co.

Flow of Fluids Through Valves, Fittings, and Pipe, Technical Paper No. 410, Crane Co., Joliet, IL, 1988

Page 4-6, example 4-10

Steam flow - Example does not specify the heat transfer conditions, so it was assumed adiabatic in this model

See Verify3.doc MS Word file for comparison with published results

Title: Verify3.aro - Steam flow in a pipe, Example 4-10 from Crane page 4-6

Analysis run on: 12/7/99 10:04:11 AM

Input File: C:\AFT Products\AFT Arrow\Verification\verify3.aro

Execution Time= 0.39 seconds

Total Number Of Pressure Iterations= 0

Total Number Of Flow Iterations= 2

Total Number Of Enthalpy Iterations= 2

Number Of Pipes= 1

Number Of Junctions= 2

Length March Solution Method with Mach Number Limits

Segments Per Pipe= 10

Mach Number Increment= .01

Pressure Tolerance= .0001 relative change

Mass Flow Rate Tolerance= .0001 relative change

Enthalpy Tolerance= .0001 relative change

Flow Relaxation= .5

Pressure Relaxation= .5

Fluid Database: AFT Standard

Fluid= Steam (Simplified)

Max Fluid Temperature Data= 1500 deg. F

Min Fluid Temperature Data= 200 deg. F

Molecular Weight= 18.016 amu

Gas Constant= 0.1102 Btu/lbm-R

Critical Pressure= 3208.22 psia

Critical Temperature= 1165.09 deg. R

Acentric Factor= .344

Equation of State= Redlich-Kwong

Enthalpy Model= Generalized

Specific Heat Ratio Accuracy= High

Atmospheric Pressure= 1 atm

Gravitational Acceleration= 1 g's

Standard Pressure= 14.696 psia

Standard Temperature= 60 deg. F

Turbulent Flow Above Reynolds Number= 4000

Laminar Flow Below Reynolds Number= 2300

Specific Heat Ratio Accuracy= High

Atmospheric Pressure= 1 atm

Gravitational Acceleration= 1 g

Standard Pressure= 14.696 psia

Standard Temperature= 60 deg. F

Turbulent Flow Above Reynolds Number= 4000

Laminar Flow Below Reynolds Number= 2300

Overall Delta Pressure = -41.41 psia

Total Inflow= 25.00 lbm/sec

Total Outflow= 25.00 lbm/sec

Total Energy Inflow= 35,663 Btu/s

Total Energy Outflow= 35,663 Btu/s

Total Heat Transferred Into System= 0.000 Btu/s

Maximum Pressure is 614.7 psia at Junction 1 Inlet

Minimum Pressure is 573.1 psia at Junction 2 Inlet

Maximum Static Temperature is 851.0 deg. F at Junction 1 Inlet

Minimum Static Temperature is 848.0 deg. F at Junction 2 Inlet

Pipe Output Table

AFT Arrow 2.0 Output
Numatec Hanford Corporation

(2)

12/7/99

Verify3.aro - Steam flow in a pipe, Example 4-10 from Crane page 4-6

Pipe	dP Static Total (psid)	Mass Flow (lbm/hr)	Vel. In (feet/sec)	Vel. Out (feet/sec)	P Static In (psig)	P Static Out (psig)	T Static In (deg. F)	T Static Out (deg. F)	f	K	fL/D	fL/ D + K
1	41.59	90,000	167.0	179.2	600.0	558.4	850.0	846.8	0.01500	3.500	12.50	16.00

All Junction Table

Jct	P Static In (psia)	P Static Out (psia)	T Static In (deg. F)	T Static Out (deg. F)
1	614.7	614.7	850.0	850.0
2	573.1	573.1	846.8	846.8

TITLE: VERIFY4.ARO

REFERENCE: Crane Co., Flow of Fluids Through Valves, Fittings, and Pipe, Technical Paper No. 410, Crane Co., Joliet, IL, 1988, Page 4-9, example 4-16

GAS: Air

ASSUMPTIONS: Example does not specify the heat transfer conditions, so it was assumed isothermal in this model.

RESULTS:

Parameter	Crane	AFT Arrow 2.0
Static pressure drop (psi)	2.61	2.712
Volumetric flow rate at inlet (ft ³ /min)	20.2	20.21
Volumetric flow rate at outlet (ft ³ /min)	20.9	20.93
Velocity inlet (ft/min)	3,367	3,368
Velocity inlet (ft/min)	3,483	3,487

DISCUSSION:

Crane does not make a distinction between static and stagnation pressure, and it appears that static pressure is usually assumed. Therefore, the inlet pressure of 65 psig was assumed to be static pressure.

Note that the Crane formula underpredicts the pressure drop (by about 4%), which in most applications is not conservative.

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AFT Arrow 2.0 Input
Numatec Hanford Corporation

(1)

12/7/99 10:24 AM

Verify4.aro - Air flow in a pipe, Example 4-16 from Crane page 4-9

Crane Co.

Flow of Fluids Through Valves, Fittings, and Pipe, Technical Paper No. 410, Crane Co., Joliet, IL, 1988

Page 4-9, example 4-16

Air flow - Example does not specify the heat transfer conditions, but it appears to use isothermal so this model uses isothermal

See Verify4.doc MS Word file for comparison with published results

Title: Verify4.aro - Air flow in a pipe, Example 4-16 from Crane page 4-9

Number Of Pipes= 1

Number Of Junctions= 2

Length March Solution Method with Mach Number Limits

Segments Per Pipe= 2

Mach Number Increment= .01

Pressure Tolerance= .0001 relative change

Mass Flow Rate Tolerance= .0001 relative change

Enthalpy Tolerance= .0001 relative change

Concentration Tolerance= .0001 relative change

Flow Relaxation= (Automatic)

Pressure Relaxation= (Automatic)

Fluid Database: AFT Standard

Fluid= Air

Max Fluid Temperature Data= 1000 deg. K

Min Fluid Temperature Data= 200 deg. K

Molecular Weight= 28.97 amu

Gas Constant= 0.06855 Btu/lbm-R

Critical Pressure= 37.25 atm

Critical Temperature= 132.41 deg. K

Acentric Factor= .021

Equation of State= Ideal Gas

Enthalpy Model= Reference

Specific Heat Ratio Accuracy= High

Atmospheric Pressure= 1 atm

Gravitational Acceleration= 1 g's

Standard Pressure= 14.696 psia

Standard Temperature= 60 deg. F

Turbulent Flow Above Reynolds Number= 4000

Laminar Flow Below Reynolds Number= 2300

Specific Heat Ratio Accuracy= High

Atmospheric Pressure= 1 atm

Gravitational Acceleration= 1 g

Standard Pressure= 14.696 psia

Standard Temperature= 60 deg. F

Turbulent Flow Above Reynolds Number= 4000

Laminar Flow Below Reynolds Number= 2300

Pipe Input Table

Pipe	Name	Pipe Defined	Length	Length Units	Hydraulic Diameter	Hydraulic Diam. Units	Roughness	Roughness Units	Losses (K)	Initial Flow
1	Pipe	Yes	75	feet	1.049	inches	0.00015	feet	0	

Pipe	Initial Flow Units	Junctions (Up,Down)	Geometry	Material	Size	Type	Special Condition
1		1, 2	Cylindrical Pipe	Steel	1 inch	schedule 40	None

Assigned Flow Table

AFT Arrow 2.0 Input
Numatec Hanford Corporation

(2)

12/7/99 10:24 AM

Verify4.aro - Air flow in a pipe, Example 4-16 from Crane page 4-9

Assigned Flow	Name	Object Defined	Database Source	Special Condition	Fluid	Type	Flow	Flow Units	Temperature	Temperature Units
2	Assigned Flow	Yes		None	Air	Outflow	100	scfm	110	deg. F

Assigned Flow	Loss Model
2	0

Assigned Pressure Table

Assigned Pressure	Name	Object Defined	Database Source	Special Condition	Fluid	Pressure	Pressure Units	Temperature
1	Assigned Pressure	Yes		N/A	Air	65	psig	110

Assigned Pressure	Temperature Units	Loss Factor
1	deg. F	0

AFT Arrow 2.0 Output
Numatec Hanford Corporation

(1)

12/7/99

Verify4.aro - Air flow in a pipe, Example 4-16 from Crane page 4-9

Crane Co.

Flow of Fluids Through Valves, Fittings, and Pipe, Technical Paper No. 410, Crane Co., Joliet, IL, 1988

Page 4-9, example 4-16

Air flow - Example does not specify the heat transfer conditions, but it appears to use isothermal so this model uses isothermal

See Verify4.doc MS Word file for comparison with published results

Title: Verify4.aro - Air flow in a pipe, Example 4-16 from Crane page 4-9

Analysis run on: 12/7/99 10:22:33 AM

Input File: C:\AFT Products\AFT Arrow\Verification\verify4.aro

Execution Time= 0.17 seconds

Total Number Of Pressure Iterations= 0

Total Number Of Flow Iterations= 2

Total Number Of Enthalpy Iterations= 2

Number Of Pipes= 1

Number Of Junctions= 2

Length March Solution Method with Mach Number Limits

Segments Per Pipe= 2

Mach Number Increment= .01

Pressure Tolerance= .0001 relative change

Mass Flow Rate Tolerance= .0001 relative change

Enthalpy Tolerance= .0001 relative change

Flow Relaxation= (Automatic)

Pressure Relaxation= (Automatic)

Fluid Database: AFT Standard

Fluid= Air

Max Fluid Temperature Data= 1000 deg. K

Min Fluid Temperature Data= 200 deg. K

Molecular Weight= 28.97 amu

Gas Constant= 0.06855 Btu/lbm-R

Critical Pressure= 37.25 atm

Critical Temperature= 132.41 deg. K

Acentric Factor= .021

Equation of State= Ideal Gas

Enthalpy Model= Reference

Specific Heat Ratio Accuracy= High

Atmospheric Pressure= 1 atm

Gravitational Acceleration= 1 g's

Standard Pressure= 14.696 psia

Standard Temperature= 60 deg. F

Turbulent Flow Above Reynolds Number= 4000

Laminar Flow Below Reynolds Number= 2300

Specific Heat Ratio Accuracy= High

Atmospheric Pressure= 1 atm

Gravitational Acceleration= 1 g

Standard Pressure= 14.696 psia

Standard Temperature= 60 deg. F

Turbulent Flow Above Reynolds Number= 4000

Laminar Flow Below Reynolds Number= 2300

Overall Delta Pressure = -2.707 psia

Total Inflow= 0.1272 lbm/sec

Total Outflow= 0.1272 lbm/sec

Total Energy Inflow= 26.10 Btu/s

Total Energy Outflow= 26.10 Btu/s

Total Heat Transferred Into System= 5.740E-04 Btu/s

Maximum Pressure is 79.70 psia at Junction 1 Inlet

Minimum Pressure is 76.98 psia at Junction 2 Inlet

Maximum Static Temperature is 110.3 deg. F at Junction 2 Inlet

Minimum Static Temperature is 110.3 deg. F at Junction 1 Inlet

Pipe Output Table

AFT Arrow 2.0 Output
Numatec Hanford Corporation

(2)

12/7/99

Verify4.aro - Air flow in a pipe, Example 4-16 from Crane page 4-9

Pipe	dP Static Total (psid)	Vol. Flow In (ft3/min)	Vol. Flow Out (ft3/min)	Vel. In (feet/min)	Vel. Out (feet/min)	Mass Flow (scfm)	P Static In (psig)	P Static Out (psig)	T Static In (deg. F)	T Static Out (deg. F)
1	2.712	20.21	20.93	3368.	3487.	100.0	65.00	62.29	110.0	110.0

All Junction Table

Jct	P Static In (psig)	P Static Out (psig)	T Static In (deg. F)	T Static Out (deg. F)
1	65.00	65.00	110.0	110.0
2	62.29	62.29	110.0	110.0

TITLE: VERIFY5.ARO

REFERENCE: Crane Co., Flow of Fluids Through Valves, Fittings, and Pipe, Technical Paper No. 410, Crane Co., Joliet, IL, 1988, Page 4-11, example 4-18

GAS: Natural Gas (mole fractions: 75% methane, 21% ethane, and 4% propane)

ASSUMPTIONS: Isothermal flow at 40 degrees F

RESULTS:

Parameter	Crane	AFT Arrow 2.0
Mass flow rate using standard friction (MMscfd) †	107.8	123.1
Mass flow rate using Weymouth (MMscfd)	105.1	120.0*
Mass flow rate using Panhandle (MMscfd)	133.7	118.5*

† Crane's calculation uses the "Simplified Compressible Flow Formula"

* Crane uses the actual Weymouth and Panhandle equations. AFT Arrow does have these equations, but instead solves the governing mass and momentum equations over pipe sections. The AFT Arrow Weymouth and Panhandle solutions above were obtained using the Weymouth and Panhandle friction factor correlation options in AFT Arrow rather than the standard Darcy-Weisbach friction factor (as used in the first case above).

DISCUSSION:

The mixture properties for this example offer an opportunity to use the Chempak mixture capabilities. The problem statement does not say whether the fractions are on a mass or mole basis, but it does say in Crane that the mixture molecular weight is 20.1. This is consistent with mole fraction. AFT Arrow's output indicates the molecular weight of the mixture is 20.11.

As noted above (*), AFT Arrow has optional friction factor models for Weymouth and Panhandle (see Crane, page 1-8 or AFT Arrow documentation). These were used for the second and third cases above. However, regardless of what friction factor model is used, AFT Arrow differs from any of the three methods above in that it directly solves the governing equations and it does so over pipe segments. In this model, the pipe was broken into 100 segments.

Since it can be easily demonstrated that AFT Arrow's solution satisfies the mass and momentum equations for this pipe, and the solution differs from the Crane solutions, the Crane solutions do not offer a mass and/or momentum balance.

TITLE: VERIFY6.ARO

REFERENCE: Crane Co., Flow of Fluids Through Valves, Fittings, and Pipe, Technical Paper No. 410, Crane Co., Joliet, IL, 1988, Page 4-13, example 4-20

GAS: Steam

ASSUMPTIONS: Example does not specify the heat transfer conditions, but it appears from the calculation procedure that adiabatic flow is assumed. The AFT Arrow model assumes adiabatic.

RESULTS:

Parameter	Crane Modified Darcy Formula	Crane Sonic Velocity Formula	AFT Arrow 2.0
Mass flow rate (lbm/hr)	11,780	11,180	11,042
Exit static enthalpy (Btu/lbm)	N/A	1,196	1,147.6
Exit static temperature (deg. F)	N/A	317	240.7

DISCUSSION:

Crane does not make a distinction between static and stagnation pressure, and it appears that static pressure is usually assumed. However, the problem statement is that the source steam comes from a header, where conditions are more likely stagnation. Therefore, stagnation pressure was assumed in the AFT Arrow model.

The Crane Sonic Velocity Formula yields a flow rate prediction that agrees well with the AFT Arrow prediction. The Crane Modified Darcy Formula appears to yield flow rates that are too high. If the inlet conditions in the AFT Arrow model are changed to static, the AFT Arrow flow rate prediction increases slightly to 11,359 (lbm/hr). AFT Arrow uses real gas properties for the steam as specified in the System Properties window.

The Crane sonic calculation assumes an isenthalpic process, which is why the exit static enthalpy is assumed to be constant at 1,196 Btu/lbm. With this assumption, the exit temperature is 317 deg. F.

However, an isenthalpic assumption turns out to be poor when the Energy Equation is applied. From the First Law,

$$\dot{q} = \dot{m} \left(h_1 + \frac{V_1^2}{2} - h_2 - \frac{V_2^2}{2} \right)$$

If the process is adiabatic, the heat transfer is zero and therefore,

$$h_2 = h_1 + \frac{V_1^2}{2} - \frac{V_2^2}{2}$$

Thus, the static enthalpy will drop because of the velocity increase. With this is accounted for, the exit static enthalpy decreases to 1148. This yields an exit static temperature of 240.7 deg. F, which is 76 degrees cooler.

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AFT Arrow 2.0 Input
Numatec Hanford Corporation

(1)

12/7/99 11:01 AM

Verify6.aro - Steam flow in a pipe, Example 4-20 from Crane page 4-13

Crane Co.
Flow of Fluids Through Valves, Fittings, and Pipe, Technical Paper No. 410, Crane Co., Joliet, IL, 1988
Page 4-13, example 4-20
Sonic choking comparison
Steam flow - Example assumes adiabatic flow

See Verify6.doc MS Word file for comparison with published results

Title: Verify6.aro - Steam flow in a pipe, Example 4-20 from Crane page 4-13

Number Of Pipes= 1
Number Of Junctions= 2

Length March Solution Method with Mach Number Limits
Segments Per Pipe= 10
Mach Number Increment= .01
Pressure Tolerance= .0001 relative change
Mass Flow Rate Tolerance= .0001 relative change
Enthalpy Tolerance= .0001 relative change
Flow Relaxation= .5
Pressure Relaxation= .5

Fluid Database: AFT Standard
Fluid= Steam (Simplified)
Max Fluid Temperature Data= 1500 deg. F
Min Fluid Temperature Data= 200 deg. F
Molecular Weight= 18.016 amu
Gas Constant= 0.110227 Btu/lbm-R
Critical Pressure= 3208.22 psia
Critical Temperature= 1165.09 deg. R
Acentric Factor= .344
Equation of State= Redlich-Kwong
Enthalpy Model= Generalized
Specific Heat Ratio Accuracy= High
Atmospheric Pressure= 1 atm
Gravitational Acceleration= 1 g's
Standard Pressure= 14.696 psia
Standard Temperature= 60 deg. F
Turbulent Flow Above Reynolds Number= 4000
Laminar Flow Below Reynolds Number= 2300
Specific Heat Ratio Accuracy= High
Atmospheric Pressure= 1 atm
Gravitational Acceleration= 1 g
Standard Pressure= 14.696 psia
Standard Temperature= 60 deg. F
Turbulent Flow Above Reynolds Number= 4000
Laminar Flow Below Reynolds Number= 2300

Pipe Input Table

Pipe	Name	Pipe Defined	Length	Length Units	Hydraulic Diameter	Hydraulic Diam. Units	Roughness	Roughness Units	Losses (K)	Initial Flow
1	Pipe	Yes	30	feet	2.067	inches	0.00015	feet	8.53	

Pipe	Initial Flow Units	Junctions (Up,Down)	Geometry	Material	Size	Type	Special Condition
1		1, 2	Cylindrical Pipe	Steel	2 inch	schedule 40	None

Tank Table

AFT Arrow 2.0 Input
Numatec Hanford Corporation

(2)

12/7/99 11:01 AM

Verify6.aro - Steam flow in a pipe, Example 4-20 from Crane page 4-13

Tank	Name	Object Defined	Database Source	Special Condition	Fluid	Pressure	Pressure Units	Temperature	Temperature Units	Balance Energy
1	Tank	Yes		N/A	Steam (Simplified)	170	psia	368.48	deg. F	No
2	Tank	Yes		N/A	Steam (Simplified)	14.7	psia	368.48	deg. F	No

Tank	Balance Concentration	(Pipe #1) K In, K Out	(Pipe #2) K In, K Out	(Pipe #3) K In, K Out	(Pipe #4) K In, K Out	(Pipe #5) K In, K Out	(Pipe #6) K In, K Out	(Pipe #7) K In, K Out	(Pipe #8) K In, K Out
1	No	(1) 0, 0							
2	No	(1) 0, 0							

Tank	(Pipe #9) K In, K Out	(Pipe #10) K In, K Out
1		
2		

AFT Arrow 2.0 Output
Numatec Hanford Corporation

(1)

12/7/99

Verify6.aro - Steam flow in a pipe, Example 4-20 from Crane page 4-13

Crane Co.

Flow of Fluids Through Valves, Fittings, and Pipe, Technical Paper No. 410, Crane Co., Joliet, IL, 1988

Page 4-13, example 4-20

Sonic choking comparison

Steam flow - Example assumes adiabatic flow

See Verify6.doc MS Word file for comparison with published results

Title: Verify6.aro - Steam flow in a pipe, Example 4-20 from Crane page 4-13

Analysis run on: 12/7/99 11:00:22 AM

Input File: C:\AFT Products\AFT Arrow\Verification\verify6.aro

Execution Time= 8.41 seconds

Total Number Of Pressure Iterations= 0

Total Number Of Flow Iterations= 3

Total Number Of Enthalpy Iterations= 3

Number Of Pipes= 1

Number Of Junctions= 2

Length March Solution Method with Mach Number Limits

Segments Per Pipe= 10

Mach Number Increment= .01

Pressure Tolerance= .0001 relative change

Mass Flow Rate Tolerance= .0001 relative change

Enthalpy Tolerance= .0001 relative change

Flow Relaxation= .5

Pressure Relaxation= .5

Fluid Database: AFT Standard

Fluid= Steam (Simplified)

Max Fluid Temperature Data= 1500 deg. F

Min Fluid Temperature Data= 200 deg. F

Molecular Weight= 18.016 amu

Gas Constant= 0.110227 Btu/lbm-R

Critical Pressure= 3208.22 psia

Critical Temperature= 1165.09 deg. R

Acentric Factor= .344

Equation of State= Redlich-Kwong

Enthalpy Model= Generalized

Specific Heat Ratio Accuracy= High

Atmospheric Pressure= 1 atm

Gravitational Acceleration= 1 g's

Standard Pressure= 14.696 psia

Standard Temperature= 60 deg. F

Turbulent Flow Above Reynolds Number= 4000

Laminar Flow Below Reynolds Number= 2300

Specific Heat Ratio Accuracy= High

Atmospheric Pressure= 1 atm

Gravitational Acceleration= 1 g

Standard Pressure= 14.696 psia

Standard Temperature= 60 deg. F

Turbulent Flow Above Reynolds Number= 4000

Laminar Flow Below Reynolds Number= 2300

Overall Delta Pressure = -155.300 psia

Total Inflow= 3.06717 lbm/sec

Total Outflow= 3.06717 lbm/sec

Total Energy Inflow= 3666.42 Btu/s

Total Energy Outflow= 3666.42 Btu/s

Total Heat Transferred Into System= 0.00000 Btu/s

Maximum Pressure is 170.000 psia at Junction 1 Inlet

Minimum Pressure is 14.7000 psia at Junction 2 Outlet

Maximum Static Temperature is 368.480 deg. F at Junction 1 Inlet

Minimum Static Temperature is 368.480 deg. F at Junction 1 Inlet

Sonic Choking Exists at Junction 2 (Tank)

Pipe Output Table

AFT Arrow 2.0 Output
Numatec Hanford Corporation

(2)

12/7/99

Verify6.aro - Steam flow in a pipe, Example 4-20 from Crane page 4-13

Pipe	Mass Flow (lbm/hr)	Vel. Out (feet/sec)	Mach # Out	P Stag. In (psia)	P Stag. Out (psia)	P Static In (psia)	P Static Out (psia)	T Static In (deg. F)	T Static Out (deg. F)	H Stag. In (Btu/lbm)	H Stag. Out (Btu/lbm)	H Static In (Btu/lbm)
1	11,041.8	1547.38	0.994833	170.000	63.0569	164.638	34.9468	362.238	240.738	1195.37	1195.37	1192.60

Pipe	H Static Out (Btu/lbm)	fL/ D + K	K	fL/D	f
1	1147.56	11.8597	8.53000	3.32974	0.0191182

All Junction Table

Jct	P Stag. In (psia)	P Stag. Out (psia)	P Static In (psia)	P Static Out (psia)	T Stag. In (deg. F)	T Stag. Out (deg. F)	T Static In (deg. F)	T Static Out (deg. F)
1	170.0000	170.0000	170.0000	170.0000	368.480	368.480	368.480	368.480
2	63.0569	14.7000	63.0569	14.7000	368.480	368.480	368.480	368.480

TITLE: VERIFY7.ARO

REFERENCE: Crane Co., Flow of Fluids Through Valves, Fittings, and Pipe, Technical Paper No. 410, Crane Co., Joliet, IL, 1988, Page 4-14, example 4-22

GAS: Air

ASSUMPTIONS: Example does not specify the heat transfer conditions. The AFT Arrow model assumes adiabatic.

RESULTS:

Parameter	Crane	AFT Arrow 2.0
Mass flow rate (scfm)	62.7	63.3

DISCUSSION:

Crane does not make a distinction between static and stagnation pressure, and it appears that static pressure is usually assumed. From the problem description, the static pressure is clearly appropriate.

The predicted flow rates agree very closely.

The Crane prediction indicates that this pipe will have subsonic velocity at the exit and hence will not choke. However, a more proper formulation of this problem shows that sonic choking will occur. This is a good example of the limitations of simplified methods such as Crane. The discrepancy comes from how to handle the exit loss of the air as it discharges to atmosphere. The Crane solution takes the appropriate K factor, equal to 1, and lumps it together with the pipe friction to obtain an overall K factor of 7.04. However, if the K factor is applied at the discharge tank and not averaged along the pipe, the flow chokes. The predicted choked flow rate is 64.3 scfm. This is not drastically different from Crane's prediction, and well within typical engineering uncertainty. But the difference, which is small here, could be larger in other applications.

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(1)

12/7/99 11:08 AM

Verify7.aro - Air flow in a pipe, Example 4-22 from Crane page 4-14

Crane Co.

Flow of Fluids Through Valves, Fittings, and Pipe, Technical Paper No. 410, Crane Co., Joliet, IL, 1988

Page 4-14, example 4-22

Air flow - Example does not specify the heat transfer conditions, so it was assumed adiabatic in this model

See Verify7.doc MS Word file for comparison with published results

Title: Verify7.aro - Air flow in a pipe, Example 4-22 from Crane page 4-14

Number Of Pipes= 1

Number Of Junctions= 2

Length March Solution Method with Mach Number Limits

Segments Per Pipe= 10

Mach Number Increment= .01

Pressure Tolerance= .0001 relative change

Mass Flow Rate Tolerance= .0001 relative change

Enthalpy Tolerance= .0001 relative change

Flow Relaxation= .5

Pressure Relaxation= .5

Fluid Database: AFT Standard

Fluid= Air

Max Fluid Temperature Data= 1000 deg. K

Min Fluid Temperature Data= 200 deg. K

Molecular Weight= 28.97 amu

Gas Constant= 0.0685486 Btu/lbm-R

Critical Pressure= 37.25 atm

Critical Temperature= 132.41 deg. K

Acentric Factor= .021

Equation of State= Redlich-Kwong

Enthalpy Model= Generalized

Specific Heat Ratio Accuracy= High

Atmospheric Pressure= 1 atm

Gravitational Acceleration= 1 g's

Standard Pressure= 14.696 psia

Standard Temperature= 60 deg. F

Turbulent Flow Above Reynolds Number= 4000

Laminar Flow Below Reynolds Number= 2300

Specific Heat Ratio Accuracy= High

Atmospheric Pressure= 1 atm

Gravitational Acceleration= 1 g

Standard Pressure= 14.696 psia

Standard Temperature= 60 deg. F

Turbulent Flow Above Reynolds Number= 4000

Laminar Flow Below Reynolds Number= 2300

Pipe Input Table

Pipe	Name	Pipe Defined	Length	Length Units	Hydraulic Diameter	Hydraulic Diam. Units	Roughness	Roughness Units	Losses (K)	Initial Flow
1	Pipe	Yes	10	feet	0.546	inches	0.00015	feet	1	

Pipe	Initial Flow Units	Junctions (Up,Down)	Geometry	Material	Size	Type	Special Condition
1		1, 2	Cylindrical Pipe	Steel	1/2 inch	schedule 80	None

Assigned Pressure Table

AFT Arrow 2.0 Input
Numatec Hanford Corporation

(2)

12/7/99 11:08 AM

Verify7.aro - Air flow in a pipe, Example 4-22 from Crane page 4-14

Assigned Pressure	Name	Object Defined	Database Source	Special Condition	Fluid	Pressure	Pressure Units	Temperature
1	Assigned Pressure	Yes		N/A	Air	19.3	psig	100
2	Assigned Pressure	Yes		N/A	Air	14.7	psia	100

Assigned Pressure	Temperature Units	Loss Factor
1	deg. F	0
2	deg. F	0

AFT Arrow 2.0 Output
Numatec Hanford Corporation

(1)

12/7/99

Verify7.aro - Air flow in a pipe, Example 4-22 from Crane page 4-14

Crane Co.

Flow of Fluids Through Valves, Fittings, and Pipe, Technical Paper No. 410, Crane Co., Joliet, IL, 1988

Page 4-14, example 4-22

Air flow - Example does not specify the heat transfer conditions, so it was assumed adiabatic in this model

See Verify7.doc MS Word file for comparison with published results

Title: Verify7.aro - Air flow in a pipe, Example 4-22 from Crane page 4-14

Analysis run on: 12/7/99 11:07:18 AM

Input File: C:\AFT Products\AFT Arrow\Verification\verify7.aro

Execution Time= 0.88 seconds

Total Number Of Pressure Iterations= 0

Total Number Of Flow Iterations= 5

Total Number Of Enthalpy Iterations= 5

Number Of Pipes= 1

Number Of Junctions= 2

Length March Solution Method with Mach Number Limits

Segments Per Pipe= 10

Mach Number Increment= .01

Pressure Tolerance= .0001 relative change

Mass Flow Rate Tolerance= .0001 relative change

Enthalpy Tolerance= .0001 relative change

Flow Relaxation= .5

Pressure Relaxation= .5

Fluid Database: AFT Standard

Fluid= Air

Max Fluid Temperature Data= 1000 deg. K

Min Fluid Temperature Data= 200 deg. K

Molecular Weight= 28.97 amu

Gas Constant= 0.0685486 Btu/lbm-R

Critical Pressure= 37.25 atm

Critical Temperature= 132.41 deg. K

Acentric Factor= .021

Equation of State= Redlich-Kwong

Enthalpy Model= Generalized

Specific Heat Ratio Accuracy= High

Atmospheric Pressure= 1 atm

Gravitational Acceleration= 1 g's

Standard Pressure= 14.696 psia

Standard Temperature= 60 deg. F

Turbulent Flow Above Reynolds Number= 4000

Laminar Flow Below Reynolds Number= 2300

Specific Heat Ratio Accuracy= High

Atmospheric Pressure= 1 atm

Gravitational Acceleration= 1 g

Standard Pressure= 14.696 psia

Standard Temperature= 60 deg. F

Turbulent Flow Above Reynolds Number= 4000

Laminar Flow Below Reynolds Number= 2300

Overall Delta Pressure = -17.0789 psia

Total Inflow= 0.0805723 lbm/sec

Total Outflow= 0.0805723 lbm/sec

Total Energy Inflow= 16.4566 Btu/s

Total Energy Outflow= 16.4566 Btu/s

Total Heat Transferred Into System= 0.00000 Btu/s

Maximum Pressure is 33.9960 psia at Junction 1 Inlet

Minimum Pressure is 14.6994 psia at Junction 2 Inlet

Maximum Static Temperature is 137.944 deg. F at Junction 2 Inlet

Minimum Static Temperature is 107.466 deg. F at Junction 1 Inlet

Pipe Output Table

AFT Arrow 2.0 Output
Numatec Hanford Corporation

(2)

12/7/99

Verify7.aro - Air flow in a pipe, Example 4-22 from Crane page 4-14

Pipe	Mass Flow (scfm)	Vel. In (feet/sec)	Vel. Out (feet/sec)	Mach # In	Mach # Out	P Static In (psia)	P Static Out (psia)	dP Static Total (psid)	T Static In (deg. F)	T Static Out (deg. F)	K	fL/D
1	63.2892	301.942	662.431	0.261373	0.588539	33.9960	14.6995	19.2965	100.000	71.0659	1.00000	6.09426

Pipe	fL/ D + K	f
1	7.09426	0.0277289

All Junction Table

Jct	P Static In (psia)	P Static Out (psia)	T Static In (deg. F)	T Static Out (deg. F)
1	33.9960	33.9960	100.0000	100.0000
2	14.6994	14.6994	99.9938	99.9938

TITLE: VERIFY8.ARO

REFERENCE: Robert W. Fox and Alan T. McDonald, Introduction to Fluid Mechanics, Third Edition, John Wiley & Sons, 1985, Pages 632-633, example 12.8

GAS: Air

ASSUMPTIONS: 1) Adiabatic flow, 2) Perfect gas.

RESULTS:

Parameter	Fox & McDonald	AFT Arrow 2.0
L_{1-3} - length to choking (meters)	4.99	4.994
V_1 - Velocity at point 1 (m/s)	65.3	65.2
T_1 - Temperature at point 1 (deg, K)	294	293.9
M_1 - Mach number at point 1	0.19	0.19
M_2 - Mach number at point 2	0.40	0.40
P_2 - Pressure at point 2 (mm Hg gage)	-18.9	-18.86*
L_{1-2} - length to measured pressure (meters)	4.29	4.29*

* AFT Arrow does not have the ability to solve for pipe length, so the length was input. With this known length, the AFT Arrow Mach number at M_2 should agree with Fox & McDonald's, and it does. The resulting mass flow rate is then used as input for AFT Arrow pipe #2.

DISCUSSION:

The predictions agree very closely.

The two pipes in the AFT Arrow model represent the solutions to stations 2 and 3.

Note that the friction factor in Fox & McDonald is the Fanning friction factor. To obtain the Darcy-Weisbach friction factor used in AFT Arrow, multiply the Fanning friction factor by 4.

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AFT Arrow 2.0 Input
Numatec Hanford Corporation

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12/7/99 11:13 AM

Verify8.aro - Air flow in a pipe, Example 12.8 from Fox & McDonald page 632-3

Robert W. Fox and Alan T. McDonald
Introduction to Fluid Mechanics, Third Edition, John Wiley & Sons, 1985
Pages 632-633, example 12.8
Air flow - The two pipes represent the solutions to stations 2 and 3.

See Verify8.doc MS Word file for comparison with published results

Title: Verify8.aro - Air flow in a pipe, Example 12.8 from Fox & McDonald page 632-3

Number Of Pipes= 2
Number Of Junctions= 3

Length March Solution Method with Mach Number Limits
Segments Per Pipe= 10
Mach Number Increment= .01
Pressure Tolerance= .0001 relative change
Mass Flow Rate Tolerance= .0001 relative change
Enthalpy Tolerance= .0001 relative change
Concentration Tolerance= .0001 relative change
Flow Relaxation= .5
Pressure Relaxation= .5

Fluid Database: AFT Standard
Fluid= Air
Max Fluid Temperature Data= 1000 deg. K
Min Fluid Temperature Data= 200 deg. K
Molecular Weight= 28.97 amu
Gas Constant= 0.06855 Btu/lbm-R
Critical Pressure= 37.25 atm
Critical Temperature= 132.41 deg. K
Acentric Factor= .021
Equation of State= Ideal Gas
Enthalpy Model= Reference
Specific Heat Ratio Accuracy= High
Atmospheric Pressure= 1 atm
Gravitational Acceleration= 1 g's
Standard Pressure= 14.696 psia
Standard Temperature= 60 deg. F
Turbulent Flow Above Reynolds Number= 4000
Laminar Flow Below Reynolds Number= 2300
Specific Heat Ratio Accuracy= High
Atmospheric Pressure= 1 atm
Gravitational Acceleration= 1 g
Standard Pressure= 14.696 psia
Standard Temperature= 60 deg. F
Turbulent Flow Above Reynolds Number= 4000
Laminar Flow Below Reynolds Number= 2300

Pipe Input Table

Pipe	Name	Pipe Defined	Length	Length Units	Hydraulic Diameter	Hydraulic Diam. Units	Roughness	Roughness Units	Losses (K)	Initial Flow
1	Pipe L 1-2	Yes	4.29	meters	7.16	mm	0.0235	Explicit f	0	
2	Pipe L 1-3	Yes	4.994	meters	7.16	mm	0.0235	Explicit f	0	

Pipe	Initial Flow Units	Junctions (Up,Down)	Geometry	Material	Size	Type	Special Condition
1		1, 2	Cylindrical Pipe	Unspecified			None
2		1, 3	Cylindrical Pipe	Unspecified			None

AFT Arrow 2.0 Input
Numatec Hanford Corporation

(2)

12/7/99 11:13 AM

Verify8.aro - Air flow in a pipe, Example 12.8 from Fox & McDonald page 632-3

Assigned Flow Table

Assigned Flow	Name	Object Defined	Database Source	Special Condition	Fluid	Type	Flow	Flow Units	Temperature
3	Location 3 - Choked	Yes		None	Air	Outflow	3.07637E-03	kg/sec	286

Assigned Flow	Temperature Units	Loss Model
3	deg. K	0

Assigned Pressure Table

Assigned Pressure	Name	Object Defined	Database Source	Special Condition	Fluid	Pressure	Pressure Units	Temperature	Temperature Units
2	Location 2	Yes		N/A	Air	-412	mm Hg (g)	296	deg. K

Assigned Pressure	Loss Factor
2	0

Tank Table

Tank	Name	Object Defined	Database Source	Special Condition	Fluid	Pressure	Pressure Units	Temperature	Temperature Units	Balance Energy
1	Supply	Yes		N/A	Air	760	mm Hg	296	deg. K	No

Tank	Balance Concentration	(Pipe #1) K In, K Out	(Pipe #2) K In, K Out	(Pipe #3) K In, K Out	(Pipe #4) K In, K Out	(Pipe #5) K In, K Out	(Pipe #6) K In, K Out	(Pipe #7) K In, K Out	(Pipe #8) K In, K Out
1	No	(1) 0, 0	(2) 0, 0						

Tank	(Pipe #9) K In, K Out	(Pipe #10) K In, K Out
1		

AFT Arrow 2.0 Output
Numatec Hanford Corporation

(1)

12/7/99

Verify8.aro - Air flow in a pipe, Example 12.8 from Fox & McDonald page 632-3

Robert W. Fox and Alan T. McDonald
Introduction to Fluid Mechanics, Third Edition, John Wiley & Sons, 1985
Pages 632-633, example 12.8
Air flow - The two pipes represent the solutions to stations 2 and 3.

See Verify8.doc MS Word file for comparison with published results

Title: Verify8.aro - Air flow in a pipe, Example 12.8 from Fox & McDonald page 632-3
Analysis run on: 12/7/99 11:13:38 AM
Input File: C:\AFT Products\AFT Arrow\Verification\verify8.aro

Execution Time= 1.10 seconds
Total Number Of Pressure Iterations= 0
Total Number Of Flow Iterations= 5
Total Number Of Enthalpy Iterations= 5
Number Of Pipes= 2
Number Of Junctions= 3

Length March Solution Method with Mach Number Limits
Segments Per Pipe= 10
Mach Number Increment= .01
Pressure Tolerance= .0001 relative change
Mass Flow Rate Tolerance= .0001 relative change
Enthalpy Tolerance= .0001 relative change
Flow Relaxation= .5
Pressure Relaxation= .5

Fluid Database: AFT Standard
Fluid= Air
Max Fluid Temperature Data= 1000 deg. K
Min Fluid Temperature Data= 200 deg. K
Molecular Weight= 28.97 amu
Gas Constant= 0.06855 Btu/lbm-R
Critical Pressure= 37.25 atm
Critical Temperature= 132.41 deg. K
Acentric Factor= .021
Equation of State= Ideal Gas
Enthalpy Model= Reference
Specific Heat Ratio Accuracy= High
Atmospheric Pressure= 1 atm
Gravitational Acceleration= 1 g's
Standard Pressure= 14.696 psia
Standard Temperature= 60 deg. F
Turbulent Flow Above Reynolds Number= 4000
Laminar Flow Below Reynolds Number= 2300
Specific Heat Ratio Accuracy= High
Atmospheric Pressure= 1 atm
Gravitational Acceleration= 1 g
Standard Pressure= 14.696 psia
Standard Temperature= 60 deg. F
Turbulent Flow Above Reynolds Number= 4000
Laminar Flow Below Reynolds Number= 2300
Total Inflow= 0.01356 lbm/sec
Total Outflow= 0.01356 lbm/sec
Total Energy Inflow= 2.660 Btu/s
Total Energy Outflow= 2.660 Btu/s
Total Heat Transferred Into System= 0.000 Btu/s

Maximum Pressure is 14.70 psia at Junction 1 Inlet
Minimum Pressure is 2.551 psia at Junction 3 Inlet
Maximum Static Temperature is 89.90 deg. F at Junction 2 Inlet
Minimum Static Temperature is 73.13 deg. F at Junction 1 Inlet

Pipe Output Table

AFT Arrow 2.0 Output
Numatec Hanford Corporation

(2)

12/7/99

Verify8.aro - Air flow in a pipe, Example 12.8 from Fox & McDonald page 632-3

Pipe	Name	Length (meters)	Mass Flow (kg/sec)	Vel. In (meters/sec)	Vel. Out (meters/sec)	Mach # In	Mach # Out	P Stag. In (mm Hg)	P Static In (mm Hg (g))	P Static Out (mm Hg (g))	T Stag. In (deg. K)
1	Pipe L 1-2	4.290	3.076E-03	65.23	135.6	0.1903	0.4005	760.0	-18.86	-412.0	296.0
2	Pipe L 1-3	4.994	3.076E-03	65.23	310.1	0.1903	0.9829	760.0	-18.86	-628.1	296.0

Pipe	T Stag. Out (deg. K)	T Static In (deg. K)	T Static Out (deg. K)	f	Rho Static In (kg/m3)
1	296.0	293.9	287.0	0.02350	1.171
2	296.1	293.9	248.7	0.02350	1.171

All Junction Table

Jct	Name	P Stag. In (mm Hg)	P Stag. Out (mm Hg)	P Static In (mm Hg)	P Static Out (mm Hg)	T Stag. In (deg. K)	T Stag. Out (deg. K)	T Static In (deg. K)	T Static Out (deg. K)
1	Supply	760.0	760.0	760.0	760.0	296.0	296.0	296.0	296.0
2	Location 2	388.4	388.4	348.0	348.0	305.3	305.3	296.0	296.0
3	Location 3 - Choked	244.4	244.4	131.9	131.9	296.1	296.1	248.7	248.7

TITLE: VERIFY9.ARO

REFERENCE: Michael R. Lindeburg, P.E., Mechanical Engineering Review Manual, Seventh Edition, Professional Publications, Belmont, CA, 1984, Pages 8-11, 8-12, example 8.12

GAS: Unspecified except that the k value (i.e., γ) is 1.4

ASSUMPTIONS: 1) Adiabatic flow, 2) Perfect gas, 3) The gas is air, but for purposes of the example it only matters that the gas has $k = 1.4$, 4) No temperature was specified, so assume 70 deg. F

RESULTS:

Parameter	Lindeburg	AFT Arrow 2.0
M_2 – Mach number at exit	0.35	0.356
P_2 – Pressure at exit (psia)	10.26	10.09

DISCUSSION:

As specified, inlet conditions are known and outlet conditions need to be determined. With the known inlet conditions, an implied mass flow rate exists. To pose the problem in AFT Arrow terms, a few simple calculations are needed to obtain the mass flow rate. Once obtained, it is applied as a flow demand at the exit.

The problem states that the inlet Mach number is 0.3, $P_1 = 12$ psia, $T_1 = 70$ F (assumed). From the ideal gas law, density, sonic speed and mass flow rate are:

$$\rho_1 = \frac{P_1}{RT_1} = \frac{(12 \text{ psia})(144 \text{ in}^2 / \text{ft}^2)}{\left(53.34 \frac{\text{ft} \cdot \text{lbf}}{\text{lbm} \cdot \text{R}}\right)(529.67 \text{ R})} = 0.06116 \text{ lbm/ft}^3$$

$$a_1 = \sqrt{\gamma RT_1} = \sqrt{1.4 \left(53.34 \frac{\text{ft} \cdot \text{lbf}}{\text{lbm} \cdot \text{R}}\right) 529.67 \text{ R}} = 1128.1 \text{ ft/s (sonic velocity)}$$

$$\dot{m} = \rho_1 V_1 A = \rho_1 (M_1 a_1) A = \left(0.06116 \frac{\text{lbm}}{\text{ft}^3}\right) (0.3) \left(1128.1 \frac{\text{ft}}{\text{s}}\right) \left(\frac{\pi}{4} 0.3^2 \text{ ft}^2\right) = 1.463 \text{ lbm/s}$$

With this flow rate at the exit, the predictions agree very closely.

Note that the friction factor in Lindeburg is the Fanning friction factor. To obtain the Darcy-Weisbach friction factor used in AFT Arrow, multiply the Fanning friction factor by 4.

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AFT Arrow 2.0 Input
Numatec Hanford Corporation

(1)

12/7/99 11:16 AM

Verify9.aro - Air flow in a pipe, Example 8.12 from Lindeburg page 8-11

Michael R. Lindeburg, P.E.

Mechanical Engineering Review Manual, Seventh Edition, Professional Publications, Belmont, CA, 1984

Pages 8-11, 8-12, example 8.12

Gas flow - Assumed to be air for this model, but for purposes of the example it only matters that the gas has $k = 1.4$

See Verify9.doc MS Word file for comparison with published results

Title: Verify9.aro - Air flow in a pipe, Example 8.12 from Lindeburg page 8-11

Number Of Pipes= 1

Number Of Junctions= 2

Length March Solution Method with Mach Number Limits

Segments Per Pipe= 10

Mach Number Increment= .01

Pressure Tolerance= .0001 relative change

Mass Flow Rate Tolerance= .0001 relative change

Enthalpy Tolerance= .0001 relative change

Concentration Tolerance= .0001 relative change

Flow Relaxation= .5

Pressure Relaxation= .5

Fluid Database: AFT Standard

Fluid= Air

Max Fluid Temperature Data= 1000 deg. K

Min Fluid Temperature Data= 200 deg. K

Molecular Weight= 28.97 amu

Gas Constant= 53.3424 ft-lbf/lbm-R

Critical Pressure= 37.25 atm

Critical Temperature= 132.41 deg. K

Acentric Factor= .021

Equation of State= Ideal Gas

Enthalpy Model= Reference

Specific Heat Ratio Accuracy= High

Atmospheric Pressure= 1 atm

Gravitational Acceleration= 1 g's

Standard Pressure= 14.696 psia

Standard Temperature= 60 deg. F

Turbulent Flow Above Reynolds Number= 4000

Laminar Flow Below Reynolds Number= 2300

Specific Heat Ratio Accuracy= High

Atmospheric Pressure= 1 atm

Gravitational Acceleration= 1 g

Standard Pressure= 14.696 psia

Standard Temperature= 60 deg. F

Turbulent Flow Above Reynolds Number= 4000

Laminar Flow Below Reynolds Number= 2300

Pipe Input Table

Pipe	Name	Pipe Defined	Length	Length Units	Hydraulic Diameter	Hydraulic Diam. Units	Roughness	Roughness Units	Losses (K)	Initial Flow
1	Pipe	Yes	50	feet	0.3	feet	0.012	Explicit f	0	

Pipe	Initial Flow Units	Junctions (Up,Down)	Geometry	Material	Size	Type	Special Condition
1		1, 2	Cylindrical Pipe	Unspecified			None

Assigned Flow Table

AFT Arrow 2.0 Input
Numatec Hanford Corporation

(2)

12/7/99 11:16 AM

Verify9.aro - Air flow in a pipe, Example 8.12 from Lindeburg page 8-11

Assigned Flow	Name	Object Defined	Database Source	Special Condition	Fluid	Type	Flow	Flow Units	Temperature
2	Assigned Flow	Yes		None	Air	Outflow	1.4626	lbm/sec	70

Assigned Flow	Temperature Units	Loss Model
2	deg. F	0

Assigned Pressure Table

Assigned Pressure	Name	Object Defined	Database Source	Special Condition	Fluid	Pressure	Pressure Units	Temperature
1	Assigned Pressure	Yes		N/A	Air	12	psia	70

Assigned Pressure	Temperature Units	Loss Factor
1	deg. F	0

AFT Arrow 2.0 Output
Numatec Hanford Corporation

(1)

12/7/99

Verify9.aro - Air flow in a pipe, Example 8.12 from Lindeburg page 8-11

Michael R. Lindeburg, P.E.

Mechanical Engineering Review Manual, Seventh Edition, Professional Publications, Belmont, CA, 1984

Pages 8-11, 8-12, example 8.12

Gas flow - Assumed to be air for this model, but for purposes of the example it only matters that the gas has $k = 1.4$

See Verify9.doc MS Word file for comparison with published results

Title: Verify9.aro - Air flow in a pipe, Example 8.12 from Lindeburg page 8-11

Analysis run on: 12/7/99 11:21:15 AM

Input File: C:\AFT Products\AFT Arrow\Verification\verify9.aro

Execution Time= 0.22 seconds

Total Number Of Pressure Iterations= 0

Total Number Of Flow Iterations= 2

Total Number Of Enthalpy Iterations= 2

Number Of Pipes= 1

Number Of Junctions= 2

Length March Solution Method with Mach Number Limits

Segments Per Pipe= 10

Mach Number Increment= .01

Pressure Tolerance= .0001 relative change

Mass Flow Rate Tolerance= .0001 relative change

Enthalpy Tolerance= .0001 relative change

Flow Relaxation= .5

Pressure Relaxation= .5

Fluid Database: AFT Standard

Fluid= Air

Max Fluid Temperature Data= 1000 deg. K

Min Fluid Temperature Data= 200 deg. K

Molecular Weight= 28.97 amu

Gas Constant= 53.3424 ft-lbf/lbm-R

Critical Pressure= 37.25 atm

Critical Temperature= 132.41 deg. K

Acentric Factor= .021

Equation of State= Ideal Gas

Enthalpy Model= Reference

Specific Heat Ratio Accuracy= High

Atmospheric Pressure= 1 atm

Gravitational Acceleration= 1 g's

Standard Pressure= 14.696 psia

Standard Temperature= 60 deg. F

Turbulent Flow Above Reynolds Number= 4000

Laminar Flow Below Reynolds Number= 2300

Specific Heat Ratio Accuracy= High

Atmospheric Pressure= 1 atm

Gravitational Acceleration= 1 g

Standard Pressure= 14.696 psia

Standard Temperature= 60 deg. F

Turbulent Flow Above Reynolds Number= 4000

Laminar Flow Below Reynolds Number= 2300

Overall Delta Pressure = -1.76057 psia

Total Inflow= 1.46260 lbm/sec

Total Outflow= 1.46260 lbm/sec

Total Energy Inflow= 289.019 Btu/s

Total Energy Outflow= 289.019 Btu/s

Total Heat Transferred Into System= 0.00000 Btu/s

Maximum Pressure is 12.0000 psia at Junction 1 Inlet

Minimum Pressure is 10.0914 psia at Junction 2 Inlet

Maximum Static Temperature is 79.3964 deg. F at Junction 2 Inlet

Minimum Static Temperature is 79.3949 deg. F at Junction 1 Inlet

Pipe Output Table

AFT Arrow 2.0 Output
Numatec Hanford Corporation

(2)

12/7/99

Verify9.ero - Air flow in a pipe, Example 8.12 from Lindeburg page 8-11

Pipe	Mach # In	Mach # Out	Mass Flow (lbm/sec)	P Static In (psia)	P Static Out (psia)	Vel. Sonic In (feet/sec)	Rho Static In (lbm/ft3)
1	0.300730	0.356346	1.46260	12.0000	10.0914	1125.00	0.0611597

All Junction Table

Jct	P Static In (psia)	P Static Out (psia)
1	12.0000	12.0000
2	10.0914	10.0914

TITLE: VERIFY10.ARO

REFERENCE: Michael R. Lindeburg, P.E., Mechanical Engineering Review Manual, Seventh Edition, Professional Publications, Belmont, CA, 1984, Pages 8-12, 8-13, example 8.14.

GAS: Methane

ASSUMPTIONS: 1) Isothermal flow, 2) Perfect gas

RESULTS:

Parameter	Lindeburg	AFT Arrow 2.0
Mass flow rate (lbm/s)	456	478

DISCUSSION:

The predictions agree closely. Part "a" makes a comparison to the Bernoulli equation, which Arrow does not solve. So part "a" was skipped.

Note that the friction factor in Lindeburg is the Fanning friction factor. To obtain the Darcy-Weisbach friction factor used in AFT Arrow, multiply the Fanning friction factor by 4.

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AFT Arrow 2.0 Input
Numatec Hanford Corporation

(1)

12/7/99 11:31 AM

Verify10.aro - Methane flow in a pipe, Example 8.13b from Lindeburg page 8-12

Michael R. Lindeburg, P.E.

Mechanical Engineering Review Manual, Seventh Edition, Professional Publications, Belmont, CA, 1984

Pages 8-12, 8-13, example 8.13b

Methane flow - Part "a" was comparing to Bernoulli, which Arrow does not solve, so it was skipped. This model applies to part "b"

See Verify10.doc MS Word file for comparison with published results

Title: Verify10.aro - Methane flow in a pipe, Example 8.13b from Lindeburg page 8-12

Number Of Pipes= 1

Number Of Junctions= 2

Length March Solution Method with Mach Number Limits

Segments Per Pipe= 10

Mach Number Increment= .01

Pressure Tolerance= .0001 relative change

Mass Flow Rate Tolerance= .0001 relative change

Enthalpy Tolerance= .0001 relative change

Flow Relaxation= .5

Pressure Relaxation= .5

Fluid Database: AFT Standard

Fluid= Methane

Max Fluid Temperature Data= 400 deg. K

Min Fluid Temperature Data= 150 deg. K

Molecular Weight= 16.043 amu

Gas Constant= 96.3243 ft-lbf/lbm-R

Critical Pressure= 4.5988 MPa

Critical Temperature= 190.555 deg. K

Acentric Factor= .008

Equation of State= Redlich-Kwong

Enthalpy Model= Generalized

Specific Heat Ratio Accuracy= High

Atmospheric Pressure= 1 atm

Gravitational Acceleration= 1 g's

Standard Pressure= 14.696 psia

Standard Temperature= 60 deg. F

Turbulent Flow Above Reynolds Number= 4000

Laminar Flow Below Reynolds Number= 2300

Specific Heat Ratio Accuracy= High

Atmospheric Pressure= 1 atm

Gravitational Acceleration= 1 g

Standard Pressure= 14.696 psia

Standard Temperature= 60 deg. F

Turbulent Flow Above Reynolds Number= 4000

Laminar Flow Below Reynolds Number= 2300

Pipe Input Table

Pipe	Name	Pipe Defined	Length	Length Units	Hydraulic Diameter	Hydraulic Diam. Units	Roughness	Roughness Units	Losses (K)	Initial Flow
1	Pipe	Yes	75	miles	40	inches	0.00936	Explicit f	0	

Pipe	Initial Flow Units	Junctions (Up,Down)	Geometry	Material	Size	Type	Special Condition
1		1, 2	Cylindrical Pipe	Unspecified			None

Assigned Pressure Table

AFT Arrow 2.0 Input
Numatec Hanford Corporation

(2)

12/7/99 11:31 AM

Verify10.aro - Methane flow in a pipe, Example 8.13b from Lindeburg page 8-12

Assigned Pressure	Name	Object Defined	Database Source	Special Condition	Fluid	Pressure	Pressure Units	Temperature
1	Assigned Pressure	Yes		N/A	Methane	650	psia	40
2	Assigned Pressure	Yes		N/A	Methane	450	psia	40

Assigned Pressure	Temperature Units	Loss Factor
1	deg. F	0
2	deg. F	0

AFT Arrow 2.0 Output
Numatec Hanford Corporation

(1)

12/7/99

Verify10.aro - Methane flow in a pipe, Example 8.13b from Lindeburg page 8-12

Michael R. Lindeburg, P.E.

Mechanical Engineering Review Manual, Seventh Edition, Professional Publications, Belmont, CA, 1984

Pages 8-12, 8-13, example 8.13b

Methane flow - Part "a" was comparing to Bernoulli, which Arrow does not solve, so it was skipped. This model applies to part "b"

See Verify10.doc MS Word file for comparison with published results

Title: Verify10.aro - Methane flow in a pipe, Example 8.13b from Lindeburg page 8-12

Analysis run on: 12/7/99 11:29:53 AM

Input File: C:\AFT Products\AFT Arrow\Verification\verify10.aro

Execution Time= 0.94 seconds

Total Number Of Pressure Iterations= 0

Total Number Of Flow Iterations= 5

Total Number Of Enthalpy Iterations= 5

Number Of Pipes= 1

Number Of Junctions= 2

Length March Solution Method with Mach Number Limits

Segments Per Pipe= 10

Mach Number Increment= .01

Pressure Tolerance= .0001 relative change

Mass Flow Rate Tolerance= .0001 relative change

Enthalpy Tolerance= .0001 relative change

Flow Relaxation= .5

Pressure Relaxation= .5

Fluid Database: AFT Standard

Fluid= Methane

Max Fluid Temperature Data= 400 deg. K

Min Fluid Temperature Data= 150 deg. K

Molecular Weight= 16.043 amu

Gas Constant= 96.3243 ft-lbf/lbm-R

Critical Pressure= 4.5988 MPa

Critical Temperature= 190.555 deg. K

Acentric Factor= .008

Equation of State= Redlich-Kwong

Enthalpy Model= Generalized

Specific Heat Ratio Accuracy= High

Atmospheric Pressure= 1 atm

Gravitational Acceleration= 1 g's

Standard Pressure= 14.696 psia

Standard Temperature= 60 deg. F

Turbulent Flow Above Reynolds Number= 4000

Laminar Flow Below Reynolds Number= 2300

Specific Heat Ratio Accuracy= High

Atmospheric Pressure= 1 atm

Gravitational Acceleration= 1 g

Standard Pressure= 14.696 psia

Standard Temperature= 60 deg. F

Turbulent Flow Above Reynolds Number= 4000

Laminar Flow Below Reynolds Number= 2300

Overall Delta Pressure = -199.926 psia

Total Inflow= 478.029 lbm/sec

Total Outflow= 478.029 lbm/sec

Total Energy Inflow= 182,233. Btu/s

Total Energy Outflow= 185,395. Btu/s

Total Heat Transferred Into System= 3161.81 Btu/s

Maximum Pressure is 650.000 psia at Junction 1 Inlet

Minimum Pressure is 450.000 psia at Junction 2 Inlet

Maximum Static Temperature is 40.0463 deg. F at Junction 2 Inlet

Minimum Static Temperature is 40.0187 deg. F at Junction 1 Inlet

Pipe Output Table

AFT Arrow 2.0 Output
Numatec Hanford Corporation

(2)

12/7/99

Verify10.aro - Methane flow in a pipe, Example 8.13b from Lindeburg page 8-12

Pipe	Mass Flow (lbm/sec)	Vel. In (feet/sec)	Vel. Out (feet/sec)	P Static In (psia)	P Static Out (psia)
1	478.029	25.3214	37.7986	650.000	449.971

All Junction Table

Jct	P Static In (psia)	P Static Out (psia)
1	650.000	650.000
2	450.000	450.000

TITLE: VERIFY11.ARO

REFERENCE: Michel A. Saad, Compressible Fluid Flow, 2nd Edition, Prentice-Hall, Englewood Cliffs, NJ, 1993, Pages 213-215, example 5.2

GAS: Air

ASSUMPTIONS: 1) Adiabatic, 2) Perfect gas

RESULTS:

Parameter	Saad	AFT Arrow 2.0
M_2 – Mach number at exit	0.685	0.689
M_1 – Mach number at inlet	0.347	0.347
P_1 – Static pressure at inlet (kPa)	306	308.1
T_1 – Static temperature at inlet (deg. K)	312.76	312.9

DISCUSSION:

As specified, exit conditions are known and inlet conditions need to be determined for specified volume flow at exit. With the known exit conditions, an implied mass flow rate exists. To pose the problem in AFT Arrow terms, a few simple calculations are needed to obtain the mass flow rate. Once obtained, it is applied as a flow demand at the inlet.

The problem states that the exit volume flow rate, Q_2 , is 1000 m³/min, $P_2 = 150$ kPa, $T_2 = 293$ K. From the ideal gas law, density, and mass flow rate are:

$$\rho_2 = \frac{P_2}{RT_2} = \frac{150 \text{ kPa}}{\left(0.2868 \frac{\text{kJ}}{\text{kg}}\right)(293 \text{ K})} = 1.784 \text{ kg/m}^3$$

$$\dot{m} = \rho_2 V_2 A = \rho_2 Q_2 = \left(1.784 \frac{\text{kg}}{\text{m}^3}\right) \left(1000 \frac{\text{m}^3}{\text{min}}\right) = 29.73 \text{ kg/s}$$

In AFT Arrow, the discharge pressure can be specified. The temperature can be specified at the exit junction, but the actual discharge is what is displayed for the pipe exit. The pipe exit temperature depends on the inlet temperature and the thermodynamic process in the pipe, which is adiabatic. Therefore, to solve this problem the inlet static temperature at J1 must be guessed until the pipe delivers 293 K at the exit. This results in the 312.9 K displayed in the above table.

All results agree closely.

Note that the friction factor in Saad is the Fanning friction factor. To obtain the Darcy-Weisbach friction factor used in AFT Arrow, multiply the Fanning friction factor by 4.

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AFT Arrow 2.0 Input
Numatec Hanford Corporation

(1)

12/7/99 11:46 AM

Verify11.aro - Air flow example 5.2 from Saad pp. 213-215

Michel A. Saad
Compressible Fluid Flow, 2nd Edition, Prentice-Hall, Englewood Cliffs, NJ, 1993
Page 213-215, example 5.2
Air flow - Example assumes adiabatic flow and air is a perfect gas

See Verify11.doc MS Word file for comparison with published results

Title: Verify11.aro - Air flow example 5.2 from Saad pp. 213-215

Number Of Pipes= 1
Number Of Junctions= 2

Length March Solution Method with Mach Number Limits
Segments Per Pipe= 10
Mach Number Increment= .01
Pressure Tolerance= .0001 relative change
Mass Flow Rate Tolerance= .0001 relative change
Enthalpy Tolerance= .0001 relative change
Flow Relaxation= .5
Pressure Relaxation= .5

Fluid Database: AFT Standard
Fluid= Air
Max Fluid Temperature Data= 1000 deg. K
Min Fluid Temperature Data= 200 deg. K
Molecular Weight= 28.97 amu
Gas Constant= 0.2868 kJ/kg-K
Critical Pressure= 37.25 atm
Critical Temperature= 132.41 deg. K
Acentric Factor= .021
Equation of State= Ideal Gas
Enthalpy Model= Reference
Specific Heat Ratio Accuracy= High
Atmospheric Pressure= 1 atm
Gravitational Acceleration= 1 g's
Standard Pressure= 14.696 psia
Standard Temperature= 60 deg. F
Turbulent Flow Above Reynolds Number= 4000
Laminar Flow Below Reynolds Number= 2300
Specific Heat Ratio Accuracy= High
Atmospheric Pressure= 1 atm
Gravitational Acceleration= 1 g
Standard Pressure= 14.696 psia
Standard Temperature= 60 deg. F
Turbulent Flow Above Reynolds Number= 4000
Laminar Flow Below Reynolds Number= 2300

Pipe Input Table

Pipe	Name	Pipe Defined	Length	Length Units	Hydraulic Diameter	Hydraulic Diam. Units	Roughness	Roughness Units	Losses (K)	Initial Flow
1	Pipe	Yes	50	meters	0.3	meters	0.02	Explicit f	0	

Pipe	Initial Flow Units	Junctions (Up,Down)	Geometry	Material	Size	Type	Special Condition
1		1, 2	Cylindrical Pipe	Unspecified			None

Assigned Flow Table

AFT Arrow 2.0 Input
Numatec Hanford Corporation

(2)

12/7/99 11:46 AM

Verify11.aio - Air flow example 5.2 from Saad pp. 213-215

Assigned Flow	Name	Object Defined	Database Source	Special Condition	Fluid	Type	Flow	Flow Units	Temperature
1	Assigned Flow	Yes		None	Air	Inflow	1783.961	kg/min	312.9

Assigned Flow	Temperature Units	Loss Model
1	deg. K	0

Assigned Pressure Table

Assigned Pressure	Name	Object Defined	Database Source	Special Condition	Fluid	Pressure	Pressure Units	Temperature
2	Assigned Pressure	Yes		N/A	Air	150	kPa	293

Assigned Pressure	Temperature Units	Loss Factor
2	deg. K	0

AFT Arrow 2.0 Output
Numatec Hanford Corporation

(1)

12/7/99

Verify11.aro - Air flow example 5.2 from Saad pp. 213-215

Michel A. Saad
Compressible Fluid Flow, 2nd Edition, Prentice-Hall, Englewood Cliffs, NJ, 1993
Page 213-215, example 5.2
Air flow - Example assumes adiabatic flow and air is a perfect gas

See Verify11.doc MS Word file for comparison with published results

Title: Verify11.aro - Air flow example 5.2 from Saad pp. 213-215
Analysis run on: 12/7/99 11:36:43 AM
Input File: C:\AFT Products\AFT Arrow\Verification\verify11.aro

Execution Time= 2.85 seconds
Total Number Of Pressure Iterations= 0
Total Number Of Flow Iterations= 2
Total Number Of Enthalpy Iterations= 2
Number Of Pipes= 1
Number Of Junctions= 2

Length March Solution Method with Mach Number Limits
Segments Per Pipe= 10
Mach Number Increment= .01
Pressure Tolerance= .0001 relative change
Mass Flow Rate Tolerance= .0001 relative change
Enthalpy Tolerance= .0001 relative change
Flow Relaxation= .5
Pressure Relaxation= .5

Fluid Database: AFT Standard
Fluid= Air
Max Fluid Temperature Data= 1000 deg. K
Min Fluid Temperature Data= 200 deg. K
Molecular Weight= 28.97 amu
Gas Constant= 0.2868 kJ/kg-K
Critical Pressure= 37.25 atm
Critical Temperature= 132.41 deg. K
Acentric Factor= .021
Equation of State= Ideal Gas
Enthalpy Model= Reference
Specific Heat Ratio Accuracy= High
Atmospheric Pressure= 1 atm
Gravitational Acceleration= 1 g's
Standard Pressure= 14.696 psia
Standard Temperature= 60 deg. F
Turbulent Flow Above Reynolds Number= 4000
Laminar Flow Below Reynolds Number= 2300
Specific Heat Ratio Accuracy= High
Atmospheric Pressure= 1 atm
Gravitational Acceleration= 1 g
Standard Pressure= 14.696 psia
Standard Temperature= 60 deg. F
Turbulent Flow Above Reynolds Number= 4000
Laminar Flow Below Reynolds Number= 2300
Overall Delta Pressure = -128.9 kPa
Total Inflow= 29.73 kg/sec
Total Outflow= 29.73 kg/sec
Total Energy Inflow= 14,287 kW
Total Energy Outflow= 14,287 kW
Total Heat Transferred Into System= 0.000 kW

Maximum Pressure is 308.0 kPa at Junction 1 Inlet
Minimum Pressure is 150.0 kPa at Junction 2 Inlet
Maximum Static Temperature is 320.3 deg. K at Junction 1 Inlet
Minimum Static Temperature is 293.0 deg. K at Junction 2 Inlet

Pipe Output Table

AFT Arrow 2.0 Output
Numatec Hanford Corporation

(2)

12/7/99

Verify11.aro - Air flow example 5.2 from Saad pp. 213-215

Pipe	Mass Flow (kg/sec)	Vel. In (meters/sec)	Vel. Out (meters/sec)	Mach # In	Mach # Out	P Static In (kPa)	P Static Out (kPa)	T Static In (deg. K)	T Static Out (deg. K)	Rho Static Out (kg/m3)
1	29.73	122.6	235.8	0.3469	0.6891	308.1	150.0	312.9	293.0	1.784

All Junction Table

Jct	P Static In (kPa)	P Static Out (kPa)	T Static In (deg. K)	T Static Out (deg. K)
1	308.0	308.0	312.9	312.9
2	150.0	150.0	268.0	268.0

TITLE: VERIFY12.ARO

REFERENCE: Michel A. Saad, Compressible Fluid Flow, 2nd Edition, Prentice-Hall, Englewood Cliffs, NJ, 1993, Pages 226-227, example 5.5

GAS: Air

ASSUMPTIONS: 1) Adiabatic, 2) Perfect gas

RESULTS:

Parameter	Saad	AFT Arrow 2.0
Mass flow rate when choked (kg/s)	2.11	2.10
M_1 – Mach number at inlet	0.603	0.604
P_1 – Static pressure at inlet (MPa)	2.106	2.114
T_1 – Static temperature at inlet (deg. K)	427.8	429.6
$P_{2,choke}$ – Static back pressure for choking (MPa)	1.203	1.217

DISCUSSION:

All results agree closely. The AFT Arrow static pressure below which choking occurs is the pipe exit static pressure.

Note that the friction factor in Saad is the Fanning friction factor. To obtain the Darcy-Weisbach friction factor used in AFT Arrow, multiply the Fanning friction factor by 4.

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AFT Arrow 2.0 Input
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(1)

12/7/99 11:54 AM

Verify12.aro - Air flow example 5.5 from Saad pp. 226-227

Michel A. Saad
Compressible Fluid Flow, 2nd Edition, Prentice-Hall, Englewood Cliffs, NJ, 1993
Page 226-227, example 5.5
Air flow - Example assumes adiabatic flow and air is a perfect gas

See Verify12.doc MS Word file for comparison with published results

Title: Verify12.aro - Air flow example 5.5 from Saad pp. 226-227

Number Of Pipes= 1
Number Of Junctions= 2

Length March Solution Method with Mach Number Limits
Segments Per Pipe= 10
Mach Number Increment= .01
Pressure Tolerance= .0001 relative change
Mass Flow Rate Tolerance= .0001 relative change
Enthalpy Tolerance= .0001 relative change
Flow Relaxation= .5
Pressure Relaxation= .5

Fluid Database: AFT Standard
Fluid= Air
Max Fluid Temperature Data= 1000 deg. K
Min Fluid Temperature Data= 200 deg. K
Molecular Weight= 28.97 amu
Gas Constant= 0.2868 kJ/kg-K
Critical Pressure= 37.25 atm
Critical Temperature= 132.41 deg. K
Acentric Factor= .021
Equation of State= Ideal Gas
Enthalpy Model= Reference
Specific Heat Ratio Accuracy= High
Atmospheric Pressure= 1 atm
Gravitational Acceleration= 1 g's
Standard Pressure= 14.696 psia
Standard Temperature= 60 deg. F
Turbulent Flow Above Reynolds Number= 4000
Laminar Flow Below Reynolds Number= 2300
Specific Heat Ratio Accuracy= High
Atmospheric Pressure= 1 atm
Gravitational Acceleration= 1 g
Standard Pressure= 14.696 psia
Standard Temperature= 60 deg. F
Turbulent Flow Above Reynolds Number= 4000
Laminar Flow Below Reynolds Number= 2300

Pipe Input Table

Pipe	Name	Pipe Defined	Length	Length Units	Hydraulic Diameter	Hydraulic Diam. Units	Roughness	Roughness Units	Losses (K)	Initial Flow
1	Pipe	Yes	0.6	meters	0.025	meters	0.02	Explicit f	0	

Pipe	Initial Flow Units	Junctions (Up,Down)	Geometry	Material	Size	Type	Special Condition
1		1, 2	Cylindrical Pipe	Unspecified			None

Assigned Pressure Table

AFT Arrow 2.0 Input
Numatec Hanford Corporation

(2)

12/7/99 11:54 AM

Verify12.aro - Air flow example 5.5 from Saad pp. 226-227

Assigned Pressure	Name	Object Defined	Database Source	Special Condition	Fluid	Pressure	Pressure Units	Temperature
1	Assigned Pressure	Yes		N/A	Air	2.7	MPa	460
2	Assigned Pressure	Yes		N/A	Air	0.1	MPa	293

Assigned Pressure	Temperature Units	Loss Factor
1	deg. K	0
2	deg. K	0

AFT Arrow 2.0 Output
Numatec Hanford Corporation

(1)

12/7/99

Verify12.aro - Air flow example 5.5 from Saad pp. 226-227

Michel A. Saad
Compressible Fluid Flow, 2nd Edition, Prentice-Hall, Englewood Cliffs, NJ, 1993
Page 226-227, example 5.5
Air flow - Example assumes adiabatic flow and air is a perfect gas

See Verify12.doc MS Word file for comparison with published results

Title: Verify12.aro - Air flow example 5.5 from Saad pp. 226-227
Analysis run on: 12/7/99 11:50:14 AM
Input File: C:\AFT Products\AFT Arrow\Verification\verify12.aro

Execution Time= 1.43 seconds
Total Number Of Pressure Iterations= 0
Total Number Of Flow Iterations= 2
Total Number Of Enthalpy Iterations= 2
Number Of Pipes= 1
Number Of Junctions= 2

Length March Solution Method with Mach Number Limits
Segments Per Pipe= 10
Mach Number Increment= .01
Pressure Tolerance= .0001 relative change
Mass Flow Rate Tolerance= .0001 relative change
Enthalpy Tolerance= .0001 relative change
Flow Relaxation= .5
Pressure Relaxation= .5

Fluid Database: AFT Standard
Fluid= Air
Max Fluid Temperature Data= 1000 deg. K
Min Fluid Temperature Data= 200 deg. K
Molecular Weight= 28.97 amu
Gas Constant= 0.2868 kJ/kg-K
Critical Pressure= 37.25 atm
Critical Temperature= 132.41 deg. K
Acentric Factor= .021
Equation of State= Ideal Gas
Enthalpy Model= Reference
Specific Heat Ratio Accuracy= High
Atmospheric Pressure= 1 atm
Gravitational Acceleration= 1 g's
Standard Pressure= 14.696 psia
Standard Temperature= 60 deg. F
Turbulent Flow Above Reynolds Number= 4000
Laminar Flow Below Reynolds Number= 2300
Specific Heat Ratio Accuracy= High
Atmospheric Pressure= 1 atm
Gravitational Acceleration= 1 g
Standard Pressure= 14.696 psia
Standard Temperature= 60 deg. F
Turbulent Flow Above Reynolds Number= 4000
Laminar Flow Below Reynolds Number= 2300
Overall Delta Pressure = -2600. kPa
Total Inflow= 2.103 kg/sec
Total Outflow= 2.103 kg/sec
Total Energy Inflow= 1311. kW
Total Energy Outflow= 1311. kW
Total Heat Transferred Into System= -2.662E-06 kW

Maximum Pressure is 2280. kPa at Junction 2 Inlet
Minimum Pressure is 100.0 kPa at Junction 2 Outlet
Maximum Static Temperature is 460.0 deg. K at Junction 1 Inlet
Minimum Static Temperature is 293.0 deg. K at Junction 2 Inlet

CAUTION Junction 2 is downstream of a shock, static properties cannot be calculated at junction.

Sonic Choking Exists at Junction 2 (Assigned Pressure)

Pipe Output Table

AFT Arrow 2.0 Output
Numatec Hanford Corporation

(2)

12/7/99

Verify12.aro - Air flow example 5.5 from Saad pp. 226-227

Pipe	Mass Flow (kg/sec)	Vel. In (meters/sec)	Vel. Out (meters/sec)	Mach # In	Mach # Out	P Static In (MPa)	P Static Out (MPa)	T Static In (deg. K)	T Static Out (deg. K)
1	2.103	249.8	389.9	0.6039	0.9939	2.114	1.217	429.6	386.0

All Junction Table

Jct	P Static In (kPa)	P Static Out (kPa)	T Static In (deg. K)	T Static Out (deg. K)
1	2114.	2114.3	429.6	429.6
2	2280.	100.0	293.0	293.0

TITLE: VERIFY13.ARO

REFERENCE: Michel A. Saad, Compressible Fluid Flow, 2nd Edition, Prentice-Hall, Englewood Cliffs, NJ, 1993, Page 270, example 6.5

GAS: Natural Gas

ASSUMPTIONS: 1) Isothermal, 2) Perfect gas, 3) Natural gas can be represented with methane

RESULTS:

Parameter	Saad	AFT Arrow 2.0
P_2 – Static pressure at exit (kPa)	263.16	262.0
M_2 – Mach number at exit	0.38	0.3818
L_{1-2} – Length to reach 500 kPa (m)	544.79	558.5
L_T^* – Length to reach sonic choke point (m)	710	709.8
P_T^* – Static pressure choke point (kPa)	114.46	114.9
M_T^* – Mach number at isothermal choke point	0.874	0.8704

DISCUSSION:

As specified, inlet conditions are known and outlet conditions need to be determined. With the known inlet conditions, an implied mass flow rate exists. To pose the problem in AFT Arrow terms, a few simple calculations are needed to obtain the mass flow rate. Once obtained, it is applied as a flow demand at the exit.

The problem states that the inlet Mach number is 0.1, $P_1 = 1$ MPa, $T_1 = 293$ K. From the ideal gas law, density, sonic speed and mass flow rate are:

$$\rho_1 = \frac{P_1}{RT_1} = \frac{1 \text{ MPa}}{\left(0.5179 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}\right)(293 \text{ K})} = 6.585 \text{ kg/m}^3$$

$$a_1 = \sqrt{\gamma RT_1} = \sqrt{1.4 \left(0.5179 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}\right) 293 \text{ K}} = 445.9 \text{ m/s (sonic velocity)}$$

$$\dot{m} = \rho_1 V_1 A = \rho_1 (M_1 a_1) A = \left(6.585 \frac{\text{kg}}{\text{m}^3}\right) (0.1) \left(445.9 \frac{\text{m}}{\text{s}}\right) \left(\frac{\pi}{4} 0.08^2 \text{ m}^2\right) = 1.4764 \text{ kg/s}$$

The first pipe represents the pipe from point 1 to 2. The second pipe represents the pipe from point 1 to the choking point. AFT Arrow does not solve for pipe length. To obtain the maximum pipe length, different lengths must be guessed with lengths that exceed sonic flow discarded.

All results agree closely. The AFT Arrow static pressure below which choking occurs is the pipe exit static pressure.

Note that the friction factor in Saad is the Fanning friction factor. To obtain the Darcy-Weisbach friction factor used in AFT Arrow, multiply the Fanning friction factor by 4.

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AFT Arrow 2.0 Input
Numatec Hanford Corporation

(1)

12/7/99 11:59 AM

Verify13.aro Natural Gas flow example 6.5 from Saad pp. 270

Michel A. Saad
Compressible Fluid Flow, 2nd Edition, Prentice-Hall, Englewood Cliffs, NJ, 1993
Page 270, example 6.5
Natural Gas flow - Isothermal flow, perfect gas, assumed to be methane

See Verify13.doc MS Word file for comparison with published results

Title: Verify13.aro Natural Gas flow example 6.5 from Saad pp. 270

Number Of Pipes= 2

Number Of Junctions= 4

Length March Solution Method with Mach Number Limits

Segments Per Pipe= 50

Mach Number Increment= .01

Pressure Tolerance= .0001 relative change

Mass Flow Rate Tolerance= .0001 relative change

Enthalpy Tolerance= .0001 relative change

Flow Relaxation= .5

Pressure Relaxation= .5

Fluid Database: AFT Standard

Fluid= Methane

Max Fluid Temperature Data= 400 deg. K

Min Fluid Temperature Data= 150 deg. K

Molecular Weight= 16.043 amu

Gas Constant= 0.5179 kJ/kg-K

Critical Pressure= 4.5988 MPa

Critical Temperature= 190.555 deg. K

Acentric Factor= .008

Equation of State= Ideal Gas

Enthalpy Model= Reference

Specific Heat Ratio Accuracy= High

Atmospheric Pressure= 1 atm

Gravitational Acceleration= 1 g's

Standard Pressure= 0.1 MPa

Standard Temperature= 293 deg. K

Turbulent Flow Above Reynolds Number= 4000

Laminar Flow Below Reynolds Number= 2300

Specific Heat Ratio Accuracy= High

Atmospheric Pressure= 1 atm

Gravitational Acceleration= 1 g

Standard Pressure= 0.1 MPa

Standard Temperature= 293 deg. K

Turbulent Flow Above Reynolds Number= 4000

Laminar Flow Below Reynolds Number= 2300

Pipe Input Table

Pipe	Name	Pipe Defined	Length	Length Units	Hydraulic Diameter	Hydraulic Diam. Units	Roughness	Roughness Units	Losses (K)	Initial Flow
1	L 1-2	Yes	684	meters	0.08	meters	0.008	Explicit f	0	
2	L1-Choke	Yes	709.814	meters	0.08	meters	0.008	Explicit f	0	

Pipe	Initial Flow Units	Junctions (Up,Down)	Geometry	Material	Size	Type	Special Condition
1		1, 2	Cylindrical Pipe	Unspecified			None
2		3, 4	Cylindrical Pipe	Unspecified			None

Assigned Flow Table

AFT Arrow 2.0 input
Numatec Hanford Corporation

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12/7/99 11:59 AM

Verify13.aro Natural Gas flow example 6.5 from Saad pp. 270

Assigned Flow	Name	Object Defined	Database Source	Special Condition	Fluid	Type	Flow	Flow Units	Temperature
2	Assigned Flow	Yes		None	Methane	Outflow	1.4764	kg/sec	293
4	Assigned Flow	Yes		None	Methane	Outflow	1.4764	kg/sec	293

Assigned Flow	Temperature Units	Loss Model
2	deg. K	0
4	deg. K	0

Assigned Pressure Table

Assigned Pressure	Name	Object Defined	Database Source	Special Condition	Fluid	Pressure	Pressure Units	Temperature
1	Assigned Pressure	Yes		N/A	Methane	1	MPa	293
3	Assigned Pressure	Yes		N/A	Methane	1	MPa	293

Assigned Pressure	Temperature Units	Loss Factor
1	deg. K	0
3	deg. K	0

AFT Arrow 2.0 Output
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Verify13.aro Natural Gas flow example 6.5 from Saad pp. 270

Michel A. Saad
Compressible Fluid Flow, 2nd Edition, Prentice-Hall, Englewood Cliffs, NJ, 1993
Page 270, example 6.5
Natural Gas flow - Isothermal flow, perfect gas, assumed to be methane

See Verify13.doc MS Word file for comparison with published results

Title: Verify13.aro Natural Gas flow example 6.5 from Saad pp. 270
Analysis run on: 12/7/99 11:55:34 AM
Input File: C:\AFT Products\AFT Arrow\Verification\verify13.aro

Execution Time= 1.60 seconds
Total Number Of Pressure Iterations= 0
Total Number Of Flow Iterations= 2
Total Number Of Enthalpy Iterations= 2
Number Of Pipes= 2
Number Of Junctions= 4

Length March Solution Method with Mach Number Limits
Segments Per Pipe= 50
Mach Number Increment= .01
Pressure Tolerance= .0001 relative change
Mass Flow Rate Tolerance= .0001 relative change
Enthalpy Tolerance= .0001 relative change
Flow Relaxation= .5
Pressure Relaxation= .5

Fluid Database: AFT Standard
Fluid= Methane
Max Fluid Temperature Data= 400 deg. K
Min Fluid Temperature Data= 150 deg. K
Molecular Weight= 16.043 amu
Gas Constant= 0.5179 kJ/kg-K
Critical Pressure= 4.5988 MPa
Critical Temperature= 190.555 deg. K
Acentric Factor= .008
Equation of State= Ideal Gas
Enthalpy Model= Reference
Specific Heat Ratio Accuracy= High
Atmospheric Pressure= 1 atm
Gravitational Acceleration= 1 g's
Standard Pressure= 0.1 MPa
Standard Temperature= 293 deg. K
Turbulent Flow Above Reynolds Number= 4000
Laminar Flow Below Reynolds Number= 2300
Specific Heat Ratio Accuracy= High
Atmospheric Pressure= 1 atm
Gravitational Acceleration= 1 g
Standard Pressure= 0.1 MPa
Standard Temperature= 293 deg. K
Turbulent Flow Above Reynolds Number= 4000
Laminar Flow Below Reynolds Number= 2300
Total Inflow= 2.953 kg/sec
Total Outflow= 2.953 kg/sec
Total Energy Inflow= 2865. kW
Total Energy Outflow= 2995. kW
Total Heat Transferred Into System= 129.6 kW

Maximum Pressure is 1.000 MPa at Junction 1 Inlet
Minimum Pressure is 0.1149 MPa at Junction 4 Inlet
Maximum Static Temperature is 54.17 deg. C at Junction 4 Inlet
Minimum Static Temperature is 20.30 deg. C at Junction 1 Inlet

Pipe Output Table

AFT Arrow 2.0 Output
Numatec Hanford Corporation

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Verify13.aro Natural Gas flow example 6.5 from Saad pp. 270

Pipe	Name	Length (meters)	Mass Flow (kg/sec)	Mach # In	Mach # Out	P Static In (kPa)	P Static Out (kPa)	T Static In (deg. K)	T Static Out (deg. K)	Gamma In	Gamma Out	Rho Static In (kg/m3)
1	L 1-2	684.0	1.476	0.1000	0.3818	1000.	262.0	293.0	293.0	1.309	1.309	6.585
2	L1-Choke	709.8	1.476	0.1000	0.8704	1000.	114.9	293.0	293.0	1.309	1.309	6.585

Pipe	Rho Static Out (kg/m3)	Vel. Sonic In (meters/sec)	Vel. Sonic Out (meters/sec)
1	1.7253	445.9	445.9
2	0.7568	445.9	445.9

Internal Pipe Results, Pipe 1, Name: L 1-2

Point	x (meters)	Mass Flow (kg/sec)	Mach #	P Static (kPa)	T Static (deg. K)	Gamma	Rho Static (kg/m3)	Vel. Sonic (meters/sec)
1	0.00	1.476	0.1000	1000.0	293.0	1.309	6.585	445.9
2	13.68	1.476	0.1009	990.9	293.0	1.309	6.525	445.9
3	27.36	1.476	0.1019	981.7	293.0	1.309	6.465	445.9
4	41.04	1.476	0.1029	972.4	293.0	1.309	6.404	445.9
5	54.72	1.476	0.1039	963.0	293.0	1.309	6.342	445.9
6	68.40	1.476	0.1049	953.5	293.0	1.309	6.279	445.9
7	82.08	1.476	0.1060	943.9	293.0	1.309	6.216	445.9
8	95.76	1.476	0.1071	934.2	293.0	1.309	6.152	445.9
9	109.44	1.476	0.1082	924.4	293.0	1.309	6.088	445.9
10	123.12	1.476	0.1094	914.5	293.0	1.309	6.023	445.9
11	136.80	1.476	0.1106	904.5	293.0	1.309	5.957	445.9
12	150.48	1.476	0.1118	894.4	293.0	1.309	5.890	445.9
13	164.16	1.476	0.1131	884.1	293.0	1.309	5.823	445.9
14	177.84	1.476	0.1145	873.8	293.0	1.309	5.754	445.9
15	191.52	1.476	0.1159	863.3	293.0	1.309	5.685	445.9
16	205.20	1.476	0.1173	852.6	293.0	1.309	5.615	445.9
17	218.88	1.476	0.1188	841.9	293.0	1.309	5.544	445.9
18	232.56	1.476	0.1204	830.9	293.0	1.309	5.472	445.9
19	246.24	1.476	0.1220	819.9	293.0	1.309	5.399	445.9
20	259.92	1.476	0.1237	808.7	293.0	1.309	5.325	445.9
21	273.60	1.476	0.1255	797.3	293.0	1.309	5.250	445.9
22	287.28	1.476	0.1273	785.7	293.0	1.309	5.174	445.9
23	300.96	1.476	0.1292	773.9	293.0	1.309	5.097	445.9
24	314.64	1.476	0.1313	762.0	293.0	1.309	5.018	445.9
25	328.32	1.476	0.1334	749.9	293.0	1.309	4.938	445.9
26	342.00	1.476	0.1356	737.5	293.0	1.309	4.857	445.9
27	355.68	1.476	0.1380	725.0	293.0	1.309	4.774	445.9
28	369.36	1.476	0.1405	712.2	293.0	1.309	4.690	445.9
29	383.04	1.476	0.1431	699.1	293.0	1.309	4.604	445.9
30	396.72	1.476	0.1458	685.8	293.0	1.309	4.517	445.9
31	410.40	1.476	0.1488	672.2	293.0	1.309	4.427	445.9
32	424.08	1.476	0.1519	658.4	293.0	1.309	4.336	445.9
33	437.76	1.476	0.1553	644.2	293.0	1.309	4.242	445.9
34	451.44	1.476	0.1589	629.6	293.0	1.309	4.146	445.9
35	465.12	1.476	0.1627	614.7	293.0	1.309	4.048	445.9
36	478.80	1.476	0.1669	599.4	293.0	1.309	3.947	445.9
37	492.48	1.476	0.1714	583.7	293.0	1.309	3.844	445.9
38	506.16	1.476	0.1763	567.5	293.0	1.309	3.737	445.9
39	519.84	1.476	0.1816	550.7	293.0	1.309	3.627	445.9

AFT Arrow 2.0 Output
Numatec Hanford Corporation

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Verify13.aro Natural Gas flow example 6.5 from Saad pp. 270

Point	x (meters)	Mass Flow (kg/sec)	Mach #	P Static (kPa)	T Static (deg. K)	Gamma	Rho Static (kg/m3)	Vel. Sonic (meters/sec)
40	533.52	1.476	0.1875	533.4	293.0	1.309	3.513	445.9
41	547.20	1.476	0.1941	515.5	293.0	1.309	3.395	445.9
42	560.88	1.476	0.2013	496.8	293.0	1.309	3.272	445.9
43	574.56	1.476	0.2096	477.3	293.0	1.309	3.143	445.9
44	588.24	1.476	0.2189	456.9	293.0	1.309	3.009	445.9
45	600.95	1.476	0.2289	436.9	293.0	1.309	2.877	445.9
46	612.03	1.476	0.2389	418.6	293.0	1.309	2.757	445.9
47	621.73	1.476	0.2489	401.8	293.0	1.309	2.646	445.9
48	630.27	1.476	0.2589	386.3	293.0	1.309	2.544	445.9
49	637.83	1.476	0.2689	371.9	293.0	1.309	2.449	445.9
50	644.53	1.476	0.2789	358.6	293.0	1.309	2.362	445.9
51	650.50	1.476	0.2889	346.2	293.0	1.309	2.280	445.9
52	655.83	1.476	0.2989	334.6	293.0	1.309	2.204	445.9
53	660.61	1.476	0.3089	323.8	293.0	1.309	2.132	445.9
54	664.91	1.476	0.3189	313.6	293.0	1.309	2.065	445.9
55	668.79	1.476	0.3289	304.1	293.0	1.309	2.003	445.9
56	672.29	1.476	0.3389	295.1	293.0	1.309	1.944	445.9
57	675.47	1.476	0.3489	286.7	293.0	1.309	1.888	445.9
58	678.35	1.476	0.3589	278.7	293.0	1.309	1.835	445.9
59	680.97	1.476	0.3689	271.1	293.0	1.309	1.785	445.9
60	683.35	1.476	0.3789	264.0	293.0	1.309	1.738	445.9
61	684.00	1.476	0.3818	262.0	293.0	1.309	1.725	445.9

Internal Pipe Results, Pipe 2, Name: L1-Choke

Point	x (meters)	Mass Flow (kg/sec)	Mach #	P Static (kPa)	T Static (deg. K)	Gamma	Rho Static (kg/m3)	Vel. Sonic (meters/sec)
1	0.00	1.476	0.1000	1000.0	293.0	1.309	6.5855	445.9
2	14.20	1.476	0.1010	990.5	293.0	1.309	6.5231	445.9
3	28.39	1.476	0.1020	981.0	293.0	1.309	6.4602	445.9
4	42.59	1.476	0.1030	971.3	293.0	1.309	6.3966	445.9
5	56.79	1.476	0.1040	961.6	293.0	1.309	6.3323	445.9
6	70.98	1.476	0.1051	951.7	293.0	1.309	6.2673	445.9
7	85.18	1.476	0.1062	941.7	293.0	1.309	6.2017	445.9
8	99.37	1.476	0.1074	931.6	293.0	1.309	6.1353	445.9
9	113.57	1.476	0.1086	921.4	293.0	1.309	6.0682	445.9
10	127.77	1.476	0.1098	911.1	293.0	1.309	6.0003	445.9
11	141.96	1.476	0.1111	900.7	293.0	1.309	5.9316	445.9
12	156.16	1.476	0.1124	890.2	293.0	1.309	5.8621	445.9
13	170.36	1.476	0.1137	879.5	293.0	1.309	5.7917	445.9
14	184.55	1.476	0.1152	868.6	293.0	1.309	5.7204	445.9
15	198.75	1.476	0.1166	857.7	293.0	1.309	5.6482	445.9
16	212.94	1.476	0.1182	846.6	293.0	1.309	5.5750	445.9
17	227.14	1.476	0.1198	835.3	293.0	1.309	5.5008	445.9
18	241.34	1.476	0.1214	823.9	293.0	1.309	5.4255	445.9
19	255.53	1.476	0.1231	812.3	293.0	1.309	5.3492	445.9
20	269.73	1.476	0.1250	800.5	293.0	1.309	5.2717	445.9
21	283.93	1.476	0.1269	788.5	293.0	1.309	5.1930	445.9
22	298.12	1.476	0.1288	776.4	293.0	1.309	5.1130	445.9
23	312.32	1.476	0.1309	764.1	293.0	1.309	5.0317	445.9
24	326.51	1.476	0.1331	751.5	293.0	1.309	4.9490	445.9
25	340.71	1.476	0.1354	738.7	293.0	1.309	4.8648	445.9

AFT Arrow 2.0 Output
Numatec Hanford Corporation

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Verify13.aro Natural Gas flow example 6.5 from Saad pp. 270

Point	x (meters)	Mass Flow (kg/sec)	Mach #	P Static (kPa)	T Static (deg. K)	Gamma	Rho Static (kg/m3)	Vel. Sonic (meters/sec)
26	354.91	1.476	0.1378	725.7	293.0	1.309	4.7790	445.9
27	369.10	1.476	0.1404	712.4	293.0	1.309	4.6916	445.9
28	383.30	1.476	0.1431	698.9	293.0	1.309	4.6025	445.9
29	397.50	1.476	0.1460	685.1	293.0	1.309	4.5115	445.9
30	411.69	1.476	0.1491	670.9	293.0	1.309	4.4185	445.9
31	425.89	1.476	0.1524	656.5	293.0	1.309	4.3234	445.9
32	440.08	1.476	0.1559	641.7	293.0	1.309	4.2260	445.9
33	454.28	1.476	0.1596	626.6	293.0	1.309	4.1262	445.9
34	468.48	1.476	0.1637	611.0	293.0	1.309	4.0237	445.9
35	482.67	1.476	0.1681	595.0	293.0	1.309	3.9183	445.9
36	496.87	1.476	0.1729	578.5	293.0	1.309	3.8098	445.9
37	511.07	1.476	0.1781	561.5	293.0	1.309	3.6978	445.9
38	525.26	1.476	0.1839	543.9	293.0	1.309	3.5820	445.9
39	539.46	1.476	0.1903	525.7	293.0	1.309	3.4619	445.9
40	553.65	1.476	0.1974	506.7	293.0	1.309	3.3371	445.9
41	567.85	1.476	0.2054	487.0	293.0	1.309	3.2069	445.9
42	582.05	1.476	0.2145	466.2	293.0	1.309	3.0704	445.9
43	595.57	1.476	0.2245	445.5	293.0	1.309	2.9336	445.9
44	607.33	1.476	0.2345	426.5	293.0	1.309	2.8086	445.9
45	617.61	1.476	0.2445	409.0	293.0	1.309	2.6937	445.9
46	626.64	1.476	0.2545	393.0	293.0	1.309	2.5879	445.9
47	634.61	1.476	0.2645	378.1	293.0	1.309	2.4901	445.9
48	641.67	1.476	0.2745	364.3	293.0	1.309	2.3994	445.9
49	647.95	1.476	0.2845	351.5	293.0	1.309	2.3150	445.9
50	653.55	1.476	0.2945	339.6	293.0	1.309	2.2365	445.9
51	658.57	1.476	0.3045	328.5	293.0	1.309	2.1630	445.9
52	663.07	1.476	0.3145	318.0	293.0	1.309	2.0942	445.9
53	667.13	1.476	0.3245	308.2	293.0	1.309	2.0297	445.9
54	670.79	1.476	0.3345	299.0	293.0	1.309	1.9690	445.9
55	674.10	1.476	0.3445	290.3	293.0	1.309	1.9119	445.9
56	677.11	1.476	0.3545	282.1	293.0	1.309	1.8580	445.9
57	679.84	1.476	0.3645	274.4	293.0	1.309	1.8070	445.9
58	682.32	1.476	0.3745	267.1	293.0	1.309	1.7588	445.9
59	684.59	1.476	0.3845	260.1	293.0	1.309	1.7130	445.9
60	686.66	1.476	0.3945	253.5	293.0	1.309	1.6696	445.9
61	688.56	1.476	0.4045	247.3	293.0	1.309	1.6283	445.9
62	690.29	1.476	0.4145	241.3	293.0	1.309	1.5891	445.9
63	691.88	1.476	0.4245	235.6	293.0	1.309	1.5516	445.9
64	693.34	1.476	0.4345	230.2	293.0	1.309	1.5159	445.9
65	694.69	1.476	0.4445	225.0	293.0	1.309	1.4818	445.9
66	695.93	1.476	0.4545	220.1	293.0	1.309	1.4492	445.9
67	697.06	1.476	0.4645	215.3	293.0	1.309	1.4180	445.9
68	698.11	1.476	0.4745	210.8	293.0	1.309	1.3881	445.9
69	699.08	1.476	0.4845	206.4	293.0	1.309	1.3595	445.9
70	699.98	1.476	0.4945	202.3	293.0	1.309	1.3320	445.9
71	700.80	1.476	0.5045	198.3	293.0	1.309	1.3056	445.9
72	701.56	1.476	0.5145	194.4	293.0	1.309	1.2802	445.9
73	702.27	1.476	0.5245	190.7	293.0	1.309	1.2558	445.9
74	702.92	1.476	0.5345	187.1	293.0	1.309	1.2323	445.9
75	703.52	1.476	0.5445	183.7	293.0	1.309	1.2097	445.9
76	704.08	1.476	0.5545	180.4	293.0	1.309	1.1879	445.9
77	704.59	1.476	0.5645	177.2	293.0	1.309	1.1668	445.9
78	705.07	1.476	0.5745	174.1	293.0	1.309	1.1465	445.9

AFT Arrow 2.0 Output
Numatec Hanford Corporation

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Verify13.aro Natural Gas flow example 6.5 from Saad pp. 270

Point	x (meters)	Mass Flow (kg/sec)	Mach #	P Static (kPa)	T Static (deg. K)	Gamma	Rho Static (kg/m3)	Vel. Sonic (meters/sec)
79	705.51	1.476	0.5845	171.1	293.0	1.309	1.1269	445.9
80	705.91	1.476	0.5945	168.2	293.0	1.309	1.1080	445.9
81	706.29	1.476	0.6045	165.5	293.0	1.309	1.0896	445.9
82	706.63	1.476	0.6145	162.8	293.0	1.309	1.0719	445.9
83	706.95	1.476	0.6245	160.2	293.0	1.309	1.0547	445.9
84	707.25	1.476	0.6345	157.6	293.0	1.309	1.0381	445.9
85	707.52	1.476	0.6445	155.2	293.0	1.309	1.0220	445.9
86	707.77	1.476	0.6545	152.8	293.0	1.309	1.0064	445.9
87	708.00	1.476	0.6645	150.5	293.0	1.309	0.9913	445.9
88	708.21	1.476	0.6745	148.3	293.0	1.309	0.9766	445.9
89	708.40	1.476	0.6845	146.1	293.0	1.309	0.9623	445.9
90	708.58	1.476	0.6945	144.0	293.0	1.309	0.9484	445.9
91	708.74	1.476	0.7045	142.0	293.0	1.309	0.9350	445.9
92	708.88	1.476	0.7145	140.0	293.0	1.309	0.9219	445.9
93	709.02	1.476	0.7245	138.1	293.0	1.309	0.9092	445.9
94	709.13	1.476	0.7345	136.2	293.0	1.309	0.8968	445.9
95	709.24	1.476	0.7445	134.3	293.0	1.309	0.8847	445.9
96	709.34	1.476	0.7545	132.6	293.0	1.309	0.8730	445.9
97	709.42	1.476	0.7645	130.8	293.0	1.309	0.8616	445.9
98	709.50	1.476	0.7745	129.1	293.0	1.309	0.8505	445.9
99	709.56	1.476	0.7845	127.5	293.0	1.309	0.8396	445.9
100	709.62	1.476	0.7945	125.9	293.0	1.309	0.8291	445.9
101	709.67	1.476	0.8045	124.3	293.0	1.309	0.8188	445.9
102	709.71	1.476	0.8145	122.8	293.0	1.309	0.8087	445.9
103	709.74	1.476	0.8245	121.3	293.0	1.309	0.7989	445.9
104	709.77	1.476	0.8345	119.9	293.0	1.309	0.7893	445.9
105	709.79	1.476	0.8445	118.4	293.0	1.309	0.7800	445.9
106	709.80	1.476	0.8545	117.1	293.0	1.309	0.7709	445.9
107	709.81	1.476	0.8645	115.7	293.0	1.309	0.7619	445.9
108	709.81	1.476	0.8704	114.9	293.0	1.309	0.7568	445.9

All Junction Table

Jct	P Static In (kPa)	P Static Out (kPa)
1	1000.0	1000.0
2	262.0	262.0
3	1000.0	1000.0
4	114.9	114.9

TITLE: VERIFY14.ARO

REFERENCE: Robert H. Perry and Don W. Green Editors, Author James. N. Tilton, Perry's Chemical Engineer's Handbook, Seventh Edition, Page 6-25, example 8

GAS: Air

ASSUMPTIONS: 1) Adiabatic, 2) Perfect gas

RESULTS:

Parameter	Tilton	AFT Arrow 2.0
Mass flow rate (kg/s)	2.7	2.716

DISCUSSION:

The objective is to solve for the choked flow rate. The results agree closely.

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AFT Arrow 2.0 Input
Numatec Hanford Corporation

(1)

12/7/99 12:12 PM

Verify14.aro - Air flow Example 8 from Perry's pp. 6-25

Robert H. Perry and Don W. Green Editors, Author James. N. Tilton
Perry's Chemical Engineer's Handbook, Seventh Edition
Page 6-25, example 8
Air flow - Adiabatic

See Verify14.doc MS Word file for comparison with published results

Title: Verify14.aro - Air flow Example 8 from Perry's pp. 6-25

Number Of Pipes= 1
Number Of Junctions= 2

Length March Solution Method with Mach Number Limits

Segments Per Pipe= 10
Mach Number Increment= .01
Pressure Tolerance= .0001 relative change
Mass Flow Rate Tolerance= .0001 relative change
Enthalpy Tolerance= .0001 relative change
Flow Relaxation= .5
Pressure Relaxation= .5

Fluid Database: AFT Standard

Fluid= Air

Max Fluid Temperature Data= 1000 deg. K

Min Fluid Temperature Data= 200 deg. K

Molecular Weight= 28.97 amu

Gas Constant= 0.2868 kJ/kg-K

Critical Pressure= 37.25 atm

Critical Temperature= 132.41 deg. K

Acentric Factor= .021

Equation of State= Ideal Gas

Enthalpy Model= Reference

Specific Heat Ratio Accuracy= Standard

Atmospheric Pressure= 1 atm

Gravitational Acceleration= 1 g's

Standard Pressure= 0.1 MPa

Standard Temperature= 293 deg. K

Turbulent Flow Above Reynolds Number= 4000

Laminar Flow Below Reynolds Number= 2300

Specific Heat Ratio Accuracy= Standard

Atmospheric Pressure= 1 atm

Gravitational Acceleration= 1 g

Standard Pressure= 0.1 MPa

Standard Temperature= 293 deg. K

Turbulent Flow Above Reynolds Number= 4000

Laminar Flow Below Reynolds Number= 2300

Pipe Input Table

Pipe	Name	Pipe Defined	Length	Length Units	Hydraulic Diameter	Hydraulic Diam. Units	Roughness	Roughness Units	Losses (K)	Initial Flow
1	Pipe	Yes	10	meters	2.067	inches	0.0188	Explicit f	2	

Pipe	Initial Flow Units	Junctions (Up,Down)	Geometry	Material	Size	Type	Special Condition
1		1, 2	Cylindrical Pipe	Steel	2 inch	schedule 40	None

Assigned Pressure Table

AFT Arrow 2.0 Input
Numatec Hanford Corporation

(2)

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Verify14.aro - Air flow Example 8 from Perry's pp. 6-25

Assigned Pressure	Name	Object Defined	Database Source	Special Condition	Fluid	Pressure	Pressure Units	Temperature
1	Assigned Pressure	Yes		N/A	Air	1	MPa (g)	20
2	Assigned Pressure	Yes		N/A	Air	1	atm	20

Assigned Pressure	Temperature Units	Loss Factor
1	deg. C	0
2	deg. C	0

AFT Arrow 2.0 Output
Numatec Hanford Corporation

(1)

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Verify14.aro - Air flow Example 8 from Perry's pp. 6-25

Robert H. Perry and Don W. Green Editors, Author James. N. Tilton
Perry's Chemical Engineer's Handbook, Seventh Edition
Page 6-25, example 8
Air flow - Adiabatic

See Verify14.doc MS Word file for comparison with published results

Title: Verify14.aro - Air flow Example 8 from Perry's pp. 6-25
Analysis run on: 12/7/99 12:13:43 PM
Input File: C:\AFT Products\AFT Arrow\Verification\verify14.aro

Execution Time= 1.65 seconds
Total Number Of Pressure Iterations= 0
Total Number Of Flow Iterations= 2
Total Number Of Enthalpy Iterations= 2
Number Of Pipes= 1
Number Of Junctions= 2

Length March Solution Method with Mach Number Limits
Segments Per Pipe= 10
Mach Number Increment= .01
Pressure Tolerance= .0001 relative change
Mass Flow Rate Tolerance= .0001 relative change
Enthalpy Tolerance= .0001 relative change
Flow Relaxation= .5
Pressure Relaxation= .5

Fluid Database: AFT Standard
Fluid= Air
Max Fluid Temperature Data= 1000 deg. K
Min Fluid Temperature Data= 200 deg. K
Molecular Weight= 28.97 amu
Gas Constant= 0.2868 kJ/kg-K
Critical Pressure= 37.25 atm
Critical Temperature= 132.41 deg. K
Acentric Factor= .021
Equation of State= Ideal Gas
Enthalpy Model= Reference
Specific Heat Ratio Accuracy= Standard
Atmospheric Pressure= 1 atm
Gravitational Acceleration= 1 g/s
Standard Pressure= 0.1 MPa
Standard Temperature= 293 deg. K
Turbulent Flow Above Reynolds Number= 4000
Laminar Flow Below Reynolds Number= 2300
Specific Heat Ratio Accuracy= Standard
Atmospheric Pressure= 1 atm
Gravitational Acceleration= 1 g
Standard Pressure= 0.1 MPa
Standard Temperature= 293 deg. K
Turbulent Flow Above Reynolds Number= 4000
Laminar Flow Below Reynolds Number= 2300
Overall Delta Pressure = -1.000 MPa
Total Inflow= 2.716 kg/sec
Total Outflow= 2.716 kg/sec
Total Energy Inflow= 1230. kW
Total Energy Outflow= 1230. kW
Total Heat Transferred Into System= 0.000 kW

Maximum Pressure is 1.037 MPa at Junction 1 Inlet
Minimum Pressure is 0.1013 MPa at Junction 2 Outlet
Maximum Static Temperature is 20.00 deg. C at Junction 1 Inlet
Minimum Static Temperature is 20.00 deg. C at Junction 1 Inlet

CAUTION Junction 2 is downstream of a shock, static properties cannot be calculated at junction.

Sonic Choking Exists at Junction 2 (Assigned Pressure)

Pipe Output Table

AFT Arrow 2.0 Output
Numatec Hanford Corporation

(2)

12/7/99

Verify14.aro - Air flow Example 8 from Perry's pp. 6-25

Pipe	Mass Flow (kg/sec)	Mach # In	Mach # Out	P Static In (kPa)	P Static Out (kPa)	T Static In (deg. K)	T Static Out (deg. K)	K	fL/D	fL/ D + K
1	2.716	0.2948	0.9946	1037.	283.5	288.2	245.4	2.000	3.581	5.581

All Junction Table

Jct	P Static In (kPa)	P Static Out (kPa)
1	1037.2	1037.2
2	532.3	101.3

TITLE: VERIFY15.ARO

REFERENCE: William S. Janna, Introduction to Fluid Mechanics, PWS Publishers, Belmont, CA 1983, Pages 317-319, example 8.8

GAS: Air

ASSUMPTIONS: 1) Adiabatic flow, 2) Perfect gas

RESULTS:

Parameter	Janna	AFT Arrow 2.0
M_2 – Mach number at exit	0.14	0.1355
P_2 – Pressure at exit (psia)	9.63	9.836
T_2 – Temperature at exit (deg. R)	528.8	528.9

DISCUSSION:

As specified, inlet conditions are known and outlet conditions need to be determined. With the known inlet conditions, an implied mass flow rate exists. To pose the problem in AFT Arrow terms, a few simple calculations are needed to obtain the mass flow rate. Once obtained, it is applied as a flow demand at the exit.

The problem states that the inlet velocity is 100 ft/s, $P_1 = 15$ psia, $T_1 = 530$ R. From the ideal gas law, density, and mass flow rate are:

$$\rho_1 = \frac{P_1}{RT_1} = \frac{15 \text{ psia}}{\left(53.34 \frac{\text{ft} \cdot \text{lbf}}{\text{lbm} \cdot \text{R}}\right)(530 \text{ R})} = 0.0764 \text{ lbm/ft}^3$$

$$\dot{m} = \rho_1 V_1 A = \rho_1 (M_1 a_1) A = \left(0.0764 \frac{\text{lbm}}{\text{ft}^3}\right) \left(100 \frac{\text{ft}}{\text{s}}\right) \left(\frac{\pi}{4} 2.067^2 \text{ in}^2\right) = 0.17814 \text{ lbm/s}$$

With this flow rate at the exit, the predictions agree very closely.

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AFT Arrow 2.0 Input
Numatec Hanford Corporation

(1)

12/7/99 12:23 PM

Verify15.aro - Air flow in a pipe, Example 8.8 from Janna page 317-319

William S. Janna
Introduction to Fluid Mechanics, PWS Publishers, Belmont, CA 1983
Pages 317-319, example 8.8
Air flow - Adiabatic flow, perfect gas assumption

See Verify15.doc MS Word file for comparison with published results

Title: Verify15.aro - Air flow in a pipe, Example 8.8 from Janna page 317-319

Number Of Pipes= 1
Number Of Junctions= 2

Length March Solution Method with Mach Number Limits
Segments Per Pipe= 2
Mach Number Increment= .01
Pressure Tolerance= .0001 relative change
Mass Flow Rate Tolerance= .0001 relative change
Enthalpy Tolerance= .0001 relative change
Flow Relaxation= (Automatic)
Pressure Relaxation= (Automatic)

Fluid Database: AFT Standard
Fluid= Air
Max Fluid Temperature Data= 1000 deg. K
Min Fluid Temperature Data= 200 deg. K
Molecular Weight= 28.97 amu
Gas Constant= 0.068549 Btu/lbm-R
Critical Pressure= 37.25 atm
Critical Temperature= 132.41 deg. K
Acentric Factor= .021
Equation of State= Ideal Gas
Enthalpy Model= Reference
Specific Heat Ratio Accuracy= High
Atmospheric Pressure= 1 atm
Gravitational Acceleration= 1 g's
Standard Pressure= 14.696 psia
Standard Temperature= 60 deg. F
Turbulent Flow Above Reynolds Number= 4000
Laminar Flow Below Reynolds Number= 2300
Specific Heat Ratio Accuracy= High
Atmospheric Pressure= 1 atm
Gravitational Acceleration= 1 g
Standard Pressure= 14.696 psia
Standard Temperature= 60 deg. F
Turbulent Flow Above Reynolds Number= 4000
Laminar Flow Below Reynolds Number= 2300

Pipe Input Table

Pipe	Name	Pipe Defined	Length	Length Units	Hydraulic Diameter	Hydraulic Diam. Units	Roughness	Roughness Units	Losses (K)	Initial Flow
1	Pipe	Yes	500	feet	2.067	inches	0.0175	Explicit f	0	

Pipe	Initial Flow Units	Junctions (Up,Down)	Geometry	Material	Size	Type	Special Condition
1		1, 2	Cylindrical Pipe	PVC	2 inch	schedule 40	None

Assigned Flow Table

AFT Arrow 2.0 Input
Numatec Hanford Corporation

(2)

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Verify15.aro - Air flow in a pipe, Example 8.8 from Janna page 317-319

Assigned Flow	Name	Object Defined	Database Source	Special Condition	Fluid	Type	Flow	Flow Units	Temperature
2	Assigned Flow	Yes		None	Air	Outflow	0.17814	lbm/sec	530

Assigned Flow	Temperature Units	Loss Model
2	deg. R	0

Assigned Pressure Table

Assigned Pressure	Name	Object Defined	Database Source	Special Condition	Fluid	Pressure	Pressure Units	Temperature
1	Assigned Pressure	Yes		N/A	Air	15	psia	530

Assigned Pressure	Temperature Units	Loss Factor
1	deg. R	0

AFT Arrow 2.0 Output
Numatec Hanford Corporation

(1)

12/7/99

Verify15.aro - Air flow in a pipe, Example 8.8 from Janna page 317-319

William S. Janna
Introduction to Fluid Mechanics, PWS Publishers, Belmont, CA 1983
Pages 317-319, example 8.8
Air flow - Adiabatic flow, perfect gas assumption

See Verify15.doc MS Word file for comparison with published results

Title: Verify15.aro - Air flow in a pipe, Example 8.8 from Janna page 317-319
Analysis run on: 12/7/99 12:22:35 PM
Input File: C:\AFT Products\AFT Arrow\Verification\verify15.aro

Execution Time= 0.16 seconds
Total Number Of Pressure Iterations= 0
Total Number Of Flow Iterations= 2
Total Number Of Enthalpy Iterations= 2
Number Of Pipes= 1
Number Of Junctions= 2

Length March Solution Method with Mach Number Limits
Segments Per Pipe= 2
Mach Number Increment= .01
Pressure Tolerance= .0001 relative change
Mass Flow Rate Tolerance= .0001 relative change
Enthalpy Tolerance= .0001 relative change
Flow Relaxation= (Automatic)
Pressure Relaxation= (Automatic)

Fluid Database: AFT Standard
Fluid= Air
Max Fluid Temperature Data= 1000 deg. K
Min Fluid Temperature Data= 200 deg. K
Molecular Weight= 28.97 amu
Gas Constant= 0.068549 Btu/lbm-R
Critical Pressure= 37.25 atm
Critical Temperature= 132.41 deg. K
Acentric Factor= .021
Equation of State= Ideal Gas
Enthalpy Model= Reference
Specific Heat Ratio Accuracy= High
Atmospheric Pressure= 1 atm
Gravitational Acceleration= 1 g's
Standard Pressure= 14.696 psia
Standard Temperature= 60 deg. F
Turbulent Flow Above Reynolds Number= 4000
Laminar Flow Below Reynolds Number= 2300
Specific Heat Ratio Accuracy= High
Atmospheric Pressure= 1 atm
Gravitational Acceleration= 1 g
Standard Pressure= 14.696 psia
Standard Temperature= 60 deg. F
Turbulent Flow Above Reynolds Number= 4000
Laminar Flow Below Reynolds Number= 2300
Overall Delta Pressure = -5.1205 psia
Total Inflow= 0.17814 lbm/sec
Total Outflow= 0.17814 lbm/sec
Total Energy Inflow= 34.844 Btu/s
Total Energy Outflow= 34.844 Btu/s
Total Heat Transferred Into System= 0.0000 Btu/s

Maximum Pressure is 15.000 psia at Junction 1 Inlet
Minimum Pressure is 9.8360 psia at Junction 2 Inlet
Maximum Static Temperature is 71.152 deg. F at Junction 2 Inlet
Minimum Static Temperature is 71.152 deg. F at Junction 1 Inlet

Pipe Output Table

AFT Arrow 2.0 Output
Numatec Hanford Corporation

(2)

12/7/99

Verify15.aro - Air flow in a pipe, Example 8.8 from Janna page 317-319

Pipe	Mach # In	Mach # Out	P Static In (psia)	P Static Out (psia)	T Static In (deg. R)	T Static Out (deg. R)	Mass Flow (lbm/sec)	Vel. In (feet/sec)	Vel. Out (feet/sec)	Rho Static In (lbm/ft3)
1	0.088913	0.13545	15.000	9.8360	530.00	528.92	0.17814	100.06	152.28	0.076402

All Junction Table

Jct	P Static In (psia)	P Static Out (psia)	T Static In (deg. F)	T Static Out (deg. F)
1	15.0000	15.0000	70.330	70.330
2	9.8360	9.8360	69.248	69.248

TITLE: VERIFY16.ARO

REFERENCE: Mohinder L. Nayyar, Piping Handbook, Sixth Edition, McGraw-Hill, New York, 1992, Page B.339, B.342, Example B8.2

GAS: Air

ASSUMPTIONS: 1) Adiabatic flow, 2) Perfect gas

RESULTS:

Parameter	Nayyar	AFT Arrow 2.0
M_1 – Mach number at valve	0.317	0.318
P_1 – Pressure at valve (psia)	128.46	128.66

DISCUSSION:

The problem assumes an unusual inlet boundary condition where the flow rate is known and the stagnation temperature. AFT Arrow uses the static temperature at the inlet because it is typically associated with a flow rate. To match the 120 F stagnation temperature, the inlet static temperature was iterated a few times.

The conditions result in sonic choking at the discharge.

The predictions agree very closely.

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AFT Arrow 2.0 Input
Numatec Hanford Corporation

(1)

12/7/99 12:25 PM

Verify16.aro - Air flow in a pipe, Example B8.2 from Nayyar Page B.339-342

Mohinder L. Nayyar
Piping Handbook, Sixth Edition, McGraw-Hill, New York, 1992
Page B.339, B.342, Example B8.2
Air flow - Example assumes air is a perfect gas and adiabatic flow

See Verify16.doc MS Word file for comparison with published results

Title: Verify16.aro - Air flow in a pipe, Example B8.2 from Nayyar Page B.339-342

Number Of Pipes= 1
Number Of Junctions= 2

Length March Solution Method with Mach Number Limits
Segments Per Pipe= 10
Mach Number Increment= .01
Pressure Tolerance= .0001 relative change
Mass Flow Rate Tolerance= .0001 relative change
Enthalpy Tolerance= .0001 relative change
Flow Relaxation= .5
Pressure Relaxation= .5

Fluid Database: AFT Standard
Fluid= Air
Max Fluid Temperature Data= 1000 deg. K
Min Fluid Temperature Data= 200 deg. K
Molecular Weight= 28.97 amu
Gas Constant= 0.0685486 Btu/lbm-R
Critical Pressure= 37.25 atm
Critical Temperature= 132.41 deg. K
Acentric Factor= .021
Equation of State= Ideal Gas
Enthalpy Model= Reference
Specific Heat Ratio Accuracy= High
Atmospheric Pressure= 1 atm
Gravitational Acceleration= 1 g's
Standard Pressure= 14.696 psia
Standard Temperature= 60 deg. F
Turbulent Flow Above Reynolds Number= 4000
Laminar Flow Below Reynolds Number= 2300
Specific Heat Ratio Accuracy= High
Atmospheric Pressure= 1 atm
Gravitational Acceleration= 1 g
Standard Pressure= 14.696 psia
Standard Temperature= 60 deg. F
Turbulent Flow Above Reynolds Number= 4000
Laminar Flow Below Reynolds Number= 2300

Pipe Input Table

Pipe	Name	Pipe Defined	Length	Length Units	Hydraulic Diameter	Hydraulic Diam. Units	Roughness	Roughness Units	Losses (K)	Initial Flow
1	Pipe	Yes	90	feet	4.026	inches	0.017	Explicit f	0	

Pipe	Initial Flow Units	Junctions (Up,Down)	Geometry	Material	Size	Type	Special Condition
1		1, 2	Cylindrical Pipe	Steel	4 inch	schedule 40	None

Assigned Flow Table

AFT Arrow 2.0 Input
Numatec Hanford Corporation

(2)

12/7/99 12:25 PM

Verify16.aro - Air flow in a pipe, Example B8.2 from Nayyar Page B.339-342

Assigned Flow	Name	Object Defined	Database Source	Special Condition	Fluid	Type	Flow	Flow Units	Temperature	Temperature Units
1	Assigned Flow	Yes		None	Air	Inflow	72000	lbm/hr	108.75	deg. F

Assigned Flow	Loss Model
1	0

Tank Table

Tank	Name	Object Defined	Database Source	Special Condition	Fluid	Pressure	Pressure Units	Temperature	Temperature Units	Balance Energy
2	Tank	Yes		N/A	Air	14.7	psia	120	deg. F	No

Tank	Balance Concentration	(Pipe #1) K In, K Out	(Pipe #2) K In, K Out	(Pipe #3) K In, K Out	(Pipe #4) K In, K Out	(Pipe #5) K In, K Out	(Pipe #6) K In, K Out	(Pipe #7) K In, K Out	(Pipe #8) K In, K Out
2	No	(1) 0, 0							

Tank	(Pipe #9) K In, K Out	(Pipe #10) K In, K Out
2		

AFT Arrow 2.0 Output
Numatec Hanford Corporation

(1)

12/7/99

Verify16.aro - Air flow in a pipe, Example B8.2 from Nayyar Page B.339-342

Mohinder L. Nayyar
Piping Handbook, Sixth Edition, McGraw-Hill, New York, 1992
Page B.339, B.342, Example B8.2
Air flow - Example assumes air is a perfect gas and adiabatic flow

See Verify16.doc MS Word file for comparison with published results

Title: Verify16.aro - Air flow in a pipe, Example B8.2 from Nayyar Page B.339-342
Analysis run on: 12/7/99 12:25:03 PM
Input File: C:\AFT Products\AFT Arrow\Verification\verify16.aro

Execution Time= 2.91 seconds
Total Number Of Pressure Iterations= 0
Total Number Of Flow Iterations= 2
Total Number Of Enthalpy Iterations= 2
Number Of Pipes= 1
Number Of Junctions= 2

Length March Solution Method with Mach Number Limits
Segments Per Pipe= 10
Mach Number Increment= .01
Pressure Tolerance= .0001 relative change
Mass Flow Rate Tolerance= .0001 relative change
Enthalpy Tolerance= .0001 relative change
Flow Relaxation= .5
Pressure Relaxation= .5

Fluid Database: AFT Standard
Fluid= Air
Max Fluid Temperature Data= 1000 deg. K
Min Fluid Temperature Data= 200 deg. K
Molecular Weight= 28.97 amu
Gas Constant= 0.0685486 Btu/lbm-R
Critical Pressure= 37.25 atm
Critical Temperature= 132.41 deg. K
Acentric Factor= .021
Equation of State= Ideal Gas
Enthalpy Model= Reference
Specific Heat Ratio Accuracy= High
Atmospheric Pressure= 1 atm
Gravitational Acceleration= 1 g's
Standard Pressure= 14.696 psia
Standard Temperature= 60 deg. F
Turbulent Flow Above Reynolds Number= 4000
Laminar Flow Below Reynolds Number= 2300
Specific Heat Ratio Accuracy= High
Atmospheric Pressure= 1 atm
Gravitational Acceleration= 1 g
Standard Pressure= 14.696 psia
Standard Temperature= 60 deg. F
Turbulent Flow Above Reynolds Number= 4000
Laminar Flow Below Reynolds Number= 2300
Overall Delta Pressure = -123.230 psia
Total Inflow= 20.0000 lbm/sec
Total Outflow= 20.0000 lbm/sec
Total Energy Inflow= 4149.85 Btu/s
Total Energy Outflow= 4149.85 Btu/s
Total Heat Transferred Into System= 0.00000 Btu/s

Maximum Pressure is 128.660 psia at Junction 1 Inlet
Minimum Pressure is 14.7000 psia at Junction 2 Outlet
Maximum Static Temperature is 120.000 deg. F at Junction 2 Inlet
Minimum Static Temperature is 119.986 deg. F at Junction 1 Inlet

Sonic Choking Exists at Junction 2 (Tank)

Pipe Output Table

AFT Arrow 2.0 Output
Numatec Hanford Corporation

(2)

12/7/99

Verify16.aro - Air flow in a pipe, Example B8.2 from Nayyar Page B.339-342

Pipe	Mass Flow (lbm/hr)	Vel. In (feet/sec)	Vel. Out (feet/sec)	Mach # In	Mach # Out	P Static In (psia)	P Static Out (psia)	T Static In (deg. F)	T Static Out (deg. F)	T Stag. In (deg. F)	T Stag. Out (deg. F)
1	72,000.0	370.246	1071.83	0.317777	0.994971	128.660	37.9497	108.750	25.6957	119.986	120.141

All Junction Table

Jct	P Static In (psia)	P Static Out (psia)	T Static In (deg. F)	T Static Out (deg. F)
1	128.6603	128.6603	108.750	108.750
2	71.2605	14.7000	120.000	120.000

TITLE: VERIFY17.ARO

REFERENCE: Mohinder L. Nayyar, Piping Handbook, Sixth Edition, McGraw-Hill, New York, 1992, Page B.342, Example B8.3

GAS: Air

ASSUMPTIONS: 1) Adiabatic flow, 2) Perfect gas

RESULTS:

Parameter	Nayyar	AFT Arrow 2.0
M_1 – Mach number at valve	0.317	0.318
P_1 – Pressure at valve (psia)	256.93	257.32

DISCUSSION:

The problem assumes an unusual inlet boundary condition where the flow rate is known and the stagnation temperature. AFT Arrow uses the static temperature at the inlet because it is typically associated with a flow rate. To match the 120 F stagnation temperature, the inlet static temperature was iterated a few times.

The conditions result in sonic choking at the discharge.

The predictions agree very closely.

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AFT Arrow 2.0 Input
Numatec Hanford Corporation

(1)

12/7/99 12:27 PM

Verify17.aro - Air flow in a pipe, Example B8.3 from Nayyar Page B.342

Mohinder L. Nayyar
Piping Handbook, Sixth Edition, McGraw-Hill, New York, 1992
Page B.342, Example B8.3
Air flow - Example assumes air is a perfect gas and adiabatic flow

See Verify17.doc MS Word file for comparison with published results

Title: Verify17.aro - Air flow in a pipe, Example B8.3 from Nayyar Page B.342

Number Of Pipes= 1

Number Of Junctions= 2

Length March Solution Method with Mach Number Limits

Segments Per Pipe= 10

Mach Number Increment= .01

Pressure Tolerance= .0001 relative change

Mass Flow Rate Tolerance= .0001 relative change

Enthalpy Tolerance= .0001 relative change

Concentration Tolerance= .0001 relative change

Flow Relaxation= .5

Pressure Relaxation= .5

Fluid Database: AFT Standard

Fluid= Air

Max Fluid Temperature Data= 1000 deg. K

Min Fluid Temperature Data= 200 deg. K

Molecular Weight= 28.97 amu

Gas Constant= 0.0685486 Btu/lbm-R

Critical Pressure= 37.25 atm

Critical Temperature= 132.41 deg. K

Acentric Factor= .021

Equation of State= Ideal Gas

Enthalpy Model= Reference

Specific Heat Ratio Accuracy= High

Atmospheric Pressure= 1 atm

Gravitational Acceleration= 1 g's

Standard Pressure= 14.696 psia

Standard Temperature= 60 deg. F

Turbulent Flow Above Reynolds Number= 4000

Laminar Flow Below Reynolds Number= 2300

Specific Heat Ratio Accuracy= High

Atmospheric Pressure= 1 atm

Gravitational Acceleration= 1 g

Standard Pressure= 14.696 psia

Standard Temperature= 60 deg. F

Turbulent Flow Above Reynolds Number= 4000

Laminar Flow Below Reynolds Number= 2300

Pipe Input Table

Pipe	Name	Pipe Defined	Length	Length Units	Hydraulic Diameter	Hydraulic Diam. Units	Roughness	Roughness Units	Losses (K)	Initial Flow
1	Pipe	Yes	90	feet	4.026	inches	0.017	Explicit f	0	

Pipe	Initial Flow Units	Junctions (Up,Down)	Geometry	Material	Size	Type	Special Condition
1		1, 2	Cylindrical Pipe	Steel	4 inch	schedule 40	None

Assigned Flow Table

AFT Arrow 2.0 Input
Numatec Hanford Corporation

(2)

12/7/99 12:27 PM

Verify17.aro - Air flow in a pipe, Example B8.3 from Nayyar Page B.342

Assigned Flow	Name	Object Defined	Database Source	Special Condition	Fluid	Type	Flow	Flow Units	Temperature	Temperature Units
1	Assigned Flow	Yes		None	Air	Inflow	144000	lbm/hr	108.75	deg. F

Assigned Flow	Loss Model
1	0

Tank Table

Tank	Name	Object Defined	Database Source	Special Condition	Fluid	Pressure	Pressure Units	Temperature	Temperature Units	Balance Energy
2	Tank	Yes		N/A	Air	14.7	psia	120	deg. F	No

Tank	Balance Concentration	(Pipe #1) K In, K Out	(Pipe #2) K In, K Out	(Pipe #3) K In, K Out	(Pipe #4) K In, K Out	(Pipe #5) K In, K Out	(Pipe #6) K In, K Out	(Pipe #7) K In, K Out	(Pipe #8) K In, K Out
2	No	(1) 0, 0							

Tank	(Pipe #9) K In, K Out	(Pipe #10) K In, K Out
2		

AFT Arrow 2.0 Output
Numatec Hanford Corporation

(1)

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Verify17.aro - Air flow in a pipe, Example B8.3 from Nayyar Page B.342

Mohinder L. Nayyar
Piping Handbook, Sixth Edition, McGraw-Hill, New York, 1992
Page B.342, Example B8.3
Air flow - Example assumes air is a perfect gas and adiabatic flow

See Verify17.doc MS Word file for comparison with published results

Title: Verify17.aro - Air flow in a pipe, Example B8.3 from Nayyar Page B.342
Analysis run on: 12/7/99 12:27:42 PM
Input File: C:\AFT Products\AFT Arrow\Verification\verify17.aro

Execution Time= 2.53 seconds
Total Number Of Pressure Iterations= 0
Total Number Of Flow Iterations= 2
Total Number Of Enthalpy Iterations= 2
Number Of Pipes= 1
Number Of Junctions= 2

Length March Solution Method with Mach Number Limits
Segments Per Pipe= 10
Mach Number Increment= .01
Pressure Tolerance= .0001 relative change
Mass Flow Rate Tolerance= .0001 relative change
Enthalpy Tolerance= .0001 relative change
Flow Relaxation= .5
Pressure Relaxation= .5

Fluid Database: AFT Standard
Fluid= Air
Max Fluid Temperature Data= 1000 deg. K
Min Fluid Temperature Data= 200 deg. K
Molecular Weight= 28.97 amu
Gas Constant= 0.0685486 Btu/lbm-R
Critical Pressure= 37.25 atm
Critical Temperature= 132.41 deg. K
Acentric Factor= .021
Equation of State= Ideal Gas
Enthalpy Model= Reference
Specific Heat Ratio Accuracy= High
Atmospheric Pressure= 1 atm
Gravitational Acceleration= 1 g/s
Standard Pressure= 14.696 psia
Standard Temperature= 60 deg. F
Turbulent Flow Above Reynolds Number= 4000
Laminar Flow Below Reynolds Number= 2300
Specific Heat Ratio Accuracy= High
Atmospheric Pressure= 1 atm
Gravitational Acceleration= 1 g
Standard Pressure= 14.696 psia
Standard Temperature= 60 deg. F
Turbulent Flow Above Reynolds Number= 4000
Laminar Flow Below Reynolds Number= 2300
Overall Delta Pressure = -261.161 psia
Total Inflow= 40.0000 lbm/sec
Total Outflow= 40.0000 lbm/sec
Total Energy Inflow= 8299.69 Btu/s
Total Energy Outflow= 8299.69 Btu/s
Total Heat Transferred Into System= 0.00000 Btu/s

Maximum Pressure is 257.321 psia at Junction 1 Inlet
Minimum Pressure is 14.7000 psia at Junction 2 Outlet
Maximum Static Temperature is 120.000 deg. F at Junction 2 Inlet
Minimum Static Temperature is 119.986 deg. F at Junction 1 Inlet

Sonic Choking Exists at Junction 2 (Tank)

Pipe Output Table

AFT Arrow 2.0 Output
Numatec Hanford Corporation

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Verify17.aro - Air flow in a pipe, Example B8.3 from Nayyar Page B.342

Pipe	Mass Flow (lbm/hr)	Vel. In (feet/sec)	Vel. Out (feet/sec)	Mach # In	Mach # Out	P Static In (psia)	P Static Out (psia)	T Static In (deg. F)	T Static Out (deg. F)	T Stag. In (deg. F)	T Stag. Out (deg. F)
1	144,000.	370.242	1066.13	0.317774	0.988658	257.323	76.4630	108.750	26.6951	119.986	120.137

All Junction Table

Jct	P Static In (psia)	P Static Out (psia)	T Static In (deg. F)	T Static Out (deg. F)
1	257.321	257.3214	108.750	108.750
2	142.534	14.7000	120.000	120.000

TITLE: VERIFY18.ARO

REFERENCE: Mohinder L. Nayyar, Piping Handbook, Sixth Edition, McGraw-Hill, New York, 1992, Page B.342, Example B8.4

GAS: Air

ASSUMPTIONS: 1) Adiabatic flow, 2) Perfect gas

RESULTS:

Parameter	Nayyar	AFT Arrow 2.0
M_1 – Mach number at valve	0.243	0.243
P_1 – Pressure at valve (psia)	168.52	168.69

DISCUSSION:

The problem assumes an unusual inlet boundary condition where the flow rate is known and the stagnation temperature. AFT Arrow uses the static temperature at the inlet because it is typically associated with a flow rate. To match the 120 F stagnation temperature, the inlet static temperature was iterated a few times.

The conditions result in sonic choking at the discharge.

The predictions agree very closely.

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AFT Arrow 2.0 Input
Numatec Hanford Corporation

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12/7/99 12:30 PM

Verify18.aro - Air flow in a pipe, Example B8.4 from Nayyar Page B.342

Mohinder L. Nayyar

Piping Handbook, Sixth Edition, McGraw-Hill, New York, 1992

Page B.342, Example B8.4

Air flow - Example assumes air is a perfect gas and adiabatic flow

See Verify18.doc MS Word file for comparison with published results

Title: Verify18.aro - Air flow in a pipe, Example B8.4 from Nayyar Page B.342

Number Of Pipes= 1

Number Of Junctions= 2

Length March Solution Method with Mach Number Limits

Segments Per Pipe= 10

Mach Number Increment= .01

Pressure Tolerance= .0001 relative change

Mass Flow Rate Tolerance= .0001 relative change

Enthalpy Tolerance= .0001 relative change

Concentration Tolerance= .0001 relative change

Flow Relaxation= .5

Pressure Relaxation= .5

Fluid Database: AFT Standard

Fluid= Air

Max Fluid Temperature Data= 1000 deg. K

Min Fluid Temperature Data= 200 deg. K

Molecular Weight= 28.97 amu

Gas Constant= 0.0685486 Btu/lbm-R

Critical Pressure= 37.25 atm

Critical Temperature= 132.41 deg. K

Acentric Factor= .021

Equation of State= Ideal Gas

Enthalpy Model= Reference

Specific Heat Ratio Accuracy= High

Atmospheric Pressure= 1 atm

Gravitational Acceleration= 1 g's

Standard Pressure= 14.696 psia

Standard Temperature= 60 deg. F

Turbulent Flow Above Reynolds Number= 4000

Laminar Flow Below Reynolds Number= 2300

Specific Heat Ratio Accuracy= High

Atmospheric Pressure= 1 atm

Gravitational Acceleration= 1 g

Standard Pressure= 14.696 psia

Standard Temperature= 60 deg. F

Turbulent Flow Above Reynolds Number= 4000

Laminar Flow Below Reynolds Number= 2300

Pipe Input Table

Pipe	Name	Pipe Defined	Length	Length Units	Hydraulic Diameter	Hydraulic Diam. Units	Roughness	Roughness Units	Losses (K)	Initial Flow
1	Pipe	Yes	180	feet	4.026	inches	0.017	Explicit f	0	

Pipe	Initial Flow Units	Junctions (Up,Down)	Geometry	Material	Size	Type	Special Condition
1		1, 2	Cylindrical Pipe	Steel	4 inch	schedule 40	None

Assigned Flow Table

AFT Arrow 2.0 Input
Numatec Hanford Corporation

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12/7/99 12:30 PM

Verify18.aro - Air flow in a pipe, Example B8.4 from Nayyar Page B.342

Assigned Flow	Name	Object Defined	Database Source	Special Condition	Fluid	Type	Flow	Flow Units	Temperature	Temperature Units
1	Assigned Flow	Yes		None	Air	Inflow	72000	lbm/hr	113.5	deg. F

Assigned Flow	Loss Model
1	0

Tank Table

Tank	Name	Object Defined	Database Source	Special Condition	Fluid	Pressure	Pressure Units	Temperature	Temperature Units	Balance Energy
2	Tank	Yes		N/A	Air	14.7	psia	120	deg. F	No

Tank	Balance Concentration	(Pipe #1) K In, K Out	(Pipe #2) K In, K Out	(Pipe #3) K In, K Out	(Pipe #4) K In, K Out	(Pipe #5) K In, K Out	(Pipe #6) K In, K Out	(Pipe #7) K In, K Out	(Pipe #8) K In, K Out
2	No	(1) 0, 0							

Tank	(Pipe #9) K In, K Out	(Pipe #10) K In, K Out
2		

AFT Arrow 2.0 Output
Numatec Hanford Corporation

(1)

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Verify18.aro - Air flow in a pipe, Example B8.4 from Nayyar Page B.342

Mohinder L. Nayyar
Piping Handbook, Sixth Edition, McGraw-Hill, New York, 1992
Page B.342, Example B8.4
Air flow - Example assumes air is a perfect gas and adiabatic flow

See Verify18.doc MS Word file for comparison with published results

Title: Verify18.aro - Air flow in a pipe, Example B8.4 from Nayyar Page B.342
Analysis run on: 12/7/99 12:29:24 PM
Input File: C:\AFT Products\AFT Arrow\Verification\verify18.aro

Execution Time= 3.13 seconds
Total Number Of Pressure Iterations= 0
Total Number Of Flow Iterations= 2
Total Number Of Enthalpy Iterations= 2
Number Of Pipes= 1
Number Of Junctions= 2

Length March Solution Method with Mach Number Limits
Segments Per Pipe= 10
Mach Number Increment= .01
Pressure Tolerance= .0001 relative change
Mass Flow Rate Tolerance= .0001 relative change
Enthalpy Tolerance= .0001 relative change
Flow Relaxation= .5
Pressure Relaxation= .5

Fluid Database: AFT Standard
Fluid= Air
Max Fluid Temperature Data= 1000 deg. K
Min Fluid Temperature Data= 200 deg. K
Molecular Weight= 28.97 amu
Gas Constant= 0.0685486 Btu/lbm-R
Critical Pressure= 37.25 atm
Critical Temperature= 132.41 deg. K
Acentric Factor= .021
Equation of State= Ideal Gas
Enthalpy Model= Reference
Specific Heat Ratio Accuracy= High
Atmospheric Pressure= 1 atm
Gravitational Acceleration= 1 g's
Standard Pressure= 14.696 psia
Standard Temperature= 60 deg. F
Turbulent Flow Above Reynolds Number= 4000
Laminar Flow Below Reynolds Number= 2300
Specific Heat Ratio Accuracy= High
Atmospheric Pressure= 1 atm
Gravitational Acceleration= 1 g
Standard Pressure= 14.696 psia
Standard Temperature= 60 deg. F
Turbulent Flow Above Reynolds Number= 4000
Laminar Flow Below Reynolds Number= 2300
Overall Delta Pressure = -161.046 psia
Total Inflow= 20.0000 lbm/sec
Total Outflow= 20.0000 lbm/sec
Total Energy Inflow= 4150.63 Btu/s
Total Energy Outflow= 4150.63 Btu/s
Total Heat Transferred Into System= 0.00000 Btu/s

Maximum Pressure is 168.690 psia at Junction 1 Inlet
Minimum Pressure is 14.7000 psia at Junction 2 Outlet
Maximum Static Temperature is 120.145 deg. F at Junction 1 Inlet
Minimum Static Temperature is 120.000 deg. F at Junction 2 Inlet

Sonic Choking Exists at Junction 2 (Tank)

Pipe Output Table

AFT Arrow 2.0 Output
Numatec Hanford Corporation

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Verify18.aro - Air flow in a pipe, Example B8.4 from Nayyar Page B.342

Pipe	Mass Flow (lbm/hr)	Vel. In (feet/sec)	Vel. Out (feet/sec)	Mach # In	Mach # Out	P Static In (psia)	P Static Out (psia)	T Static In (deg. F)	T Static Out (deg. F)	T Stag. In (deg. F)	T Stag. Out (deg. F)
1	72,000.0	284.747	1070.27	0.243388	0.993082	168.690	38.0391	113.500	26.1325	120.145	120.300

All Junction Table

Jct	P Static In (psia)	P Static Out (psia)	T Static In (deg. F)	T Static Out (deg. F)
1	168.6898	168.6898	113.500	113.500
2	71.2718	14.7000	120.000	120.000

TITLE: VERIFY19.ARO

REFERENCE: Mohinder L. Nayyar, Piping Handbook, Sixth Edition, McGraw-Hill, New York, 1992, Page B.342, Example B8.5

GAS: Air

ASSUMPTIONS: 1) Adiabatic flow, 2) Perfect gas

RESULTS:

Parameter	Nayyar	AFT Arrow 2.0
P_1 - Pressure at valve (psia)	165.29	165.60

DISCUSSION:

The problem assumes an unusual inlet boundary condition where the flow rate is known and the stagnation temperature. AFT Arrow uses the static temperature at the inlet because it is typically associated with a flow rate. To match the 500 F stagnation temperature, the inlet static temperature was iterated a few times.

The conditions result in sonic choking at the discharge.

The predictions agree very closely.

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AFT Arrow 2.0 Input
Numatec Hanford Corporation

(1)

12/20/99 10:41 AM

Verify19.aro - Air flow in a pipe, Example B8.5 from Nayyar Page B.342

Mohinder L. Nayyar
Piping Handbook, Sixth Edition, McGraw-Hill, New York, 1992
Page B.342, B.343, Example B8.5
Air flow - Example assumes air is a perfect gas and adiabatic flow

See Verify19.doc MS Word file for comparison with published results

Title: Verify19.aro - Air flow in a pipe, Example B8.5 from Nayyar Page B.342

Number Of Pipes= 1
Number Of Junctions= 2

Length March Solution Method with Mach Number Limits
Segments Per Pipe= 10
Mach Number Increment= .01
Pressure Tolerance= .0001 relative change
Mass Flow Rate Tolerance= .0001 relative change
Enthalpy Tolerance= .0001 relative change
Flow Relaxation= .5
Pressure Relaxation= .5

Fluid Database: AFT Standard
Fluid= Air
Max Fluid Temperature Data= 1000 deg. K
Min Fluid Temperature Data= 200 deg. K
Molecular Weight= 28.97 amu
Gas Constant= 0.0685486 Btu/lbm-R
Critical Pressure= 37.25 atm
Critical Temperature= 132.41 deg. K
Acentric Factor= .021
Equation of State= Ideal Gas
Enthalpy Model= Reference
Specific Heat Ratio Accuracy= High
Atmospheric Pressure= 1 atm
Gravitational Acceleration= 1 g's
Standard Pressure= 14.696 psia
Standard Temperature= 60 deg. F
Turbulent Flow Above Reynolds Number= 4000
Laminar Flow Below Reynolds Number= 2300
Specific Heat Ratio Accuracy= High
Atmospheric Pressure= 1 atm
Gravitational Acceleration= 1 g
Standard Pressure= 14.696 psia
Standard Temperature= 60 deg. F
Turbulent Flow Above Reynolds Number= 4000
Laminar Flow Below Reynolds Number= 2300

Pipe Input Table

Pipe	Name	Pipe Defined	Length	Length Units	Hydraulic Diameter	Hydraulic Diam. Units	Roughness	Roughness Units	Losses (K)	Initial Flow
1	Pipe	Yes	90	feet	4.026	inches	0.017	Explicit f	0	

Pipe	Initial Flow Units	Junctions (Up,Down)	Geometry	Material	Size	Type	Special Condition
1		1, 2	Cylindrical Pipe	Steel	4 inch	schedule 40	None

Assigned Flow Table

AFT Arrow 2.0 Input
Numatec Hanford Corporation

(2)

12/20/99 10:41 AM

Verify19.aro - Air flow in a pipe, Example B8.5 from Nayyar Page B.342

Assigned Flow	Name	Object Defined	Database Source	Special Condition	Fluid	Type	Flow	Flow Units	Temperature	Temperature Units
1	Assigned Flow	Yes		None	Air	Inflow	72000	lbm/hr	481	deg. F

Assigned Flow	Loss Model
1	0

Tank Table

Tank	Name	Object Defined	Database Source	Special Condition	Fluid	Pressure	Pressure Units	Temperature	Temperature Units	Balance Energy
2	Tank	Yes		N/A	Air	14.7	psia	120	deg. F	No

Tank	Balance Concentration	(Pipe #1) K In, K Out	(Pipe #2) K In, K Out	(Pipe #3) K In, K Out	(Pipe #4) K In, K Out	(Pipe #5) K In, K Out	(Pipe #6) K In, K Out	(Pipe #7) K In, K Out	(Pipe #8) K In, K Out
2	No	(1) 0, 0							

Tank	(Pipe #9) K In, K Out	(Pipe #10) K In, K Out
2		

AFT Arrow 2.0 Output
Numatec Hanford Corporation

(1)

12/20/99

Verify19.aro - Air flow in a pipe, Example B8.5 from Nayyar Page B.342

Mohinder L. Nayyar
Piping Handbook, Sixth Edition, McGraw-Hill, New York, 1992
Page B.342, B.343, Example B8.5
Air flow - Example assumes air is a perfect gas and adiabatic flow

See Verify19.doc MS Word file for comparison with published results

Title: Verify19.aro - Air flow in a pipe, Example B8.5 from Nayyar Page B.342
Analysis run on: 12/20/99 10:40:24 AM
Input File: C:\AFT Products\AFT Arrow\Verification\verify19.aro

Execution Time= 3.35 seconds
Total Number Of Pressure Iterations= 0
Total Number Of Flow Iterations= 2
Total Number Of Enthalpy Iterations= 2
Number Of Pipes= 1
Number Of Junctions= 2

Length March Solution Method with Mach Number Limits
Segments Per Pipe= 10
Mach Number Increment= .01
Pressure Tolerance= .0001 relative change
Mass Flow Rate Tolerance= .0001 relative change
Enthalpy Tolerance= .0001 relative change
Flow Relaxation= .5
Pressure Relaxation= .5

Fluid Database: AFT Standard
Fluid= Air
Max Fluid Temperature Data= 1000 deg. K
Min Fluid Temperature Data= 200 deg. K
Molecular Weight= 28.97 amu
Gas Constant= 0.0685486 Btu/lbm-R
Critical Pressure= 37.25 atm
Critical Temperature= 132.41 deg. K
Acentric Factor= .021
Equation of State= Ideal Gas
Enthalpy Model= Reference
Specific Heat Ratio Accuracy= High
Atmospheric Pressure= 1 atm
Gravitational Acceleration= 1 g's
Standard Pressure= 14.696 psia
Standard Temperature= 60 deg. F
Turbulent Flow Above Reynolds Number= 4000
Laminar Flow Below Reynolds Number= 2300
Specific Heat Ratio Accuracy= High
Atmospheric Pressure= 1 atm
Gravitational Acceleration= 1 g
Standard Pressure= 14.696 psia
Standard Temperature= 60 deg. F
Turbulent Flow Above Reynolds Number= 4000
Laminar Flow Below Reynolds Number= 2300
Overall Delta Pressure = -162.824 psia
Total Inflow= 20.0000 lbm/sec
Total Outflow= 20.0000 lbm/sec
Total Energy Inflow= 6011.31 Btu/s
Total Energy Outflow= 6011.31 Btu/s
Total Heat Transferred Into System= 0.00000 Btu/s

Maximum Pressure is 165.604 psia at Junction 1 Inlet
Minimum Pressure is 14.7000 psia at Junction 2 Outlet
Maximum Static Temperature is 499.335 deg. F at Junction 1 Inlet
Minimum Static Temperature is 120.000 deg. F at Junction 2 Inlet

Sonic Choking Exists at Junction 2 (Tank)

Pipe Output Table

AFT Arrow 2.0 Output
Numatec Hanford Corporation

(2)

12/20/99

Verify19.aro - Air flow in a pipe, Example B8.5 from Nayyar Page B.342

Pipe	Mass Flow (lbm/hr)	Vel. In (feet/sec)	Vel. Out (feet/sec)	Mach # In	Mach # Out	P Static In (psia)	P Static Out (psia)	T Static In (deg. F)	T Static Out (deg. F)	T Stag. In (deg. F)	T Stag. Out (deg. F)
1	72,000.0	476.028	1377.07	0.318401	0.994614	165.604	49.0050	481.000	345.576	499.335	499.740

All Junction Table

Jct	P Static In (psia)	P Static Out (psia)	T Static In (deg. F)	T Static Out (deg. F)
1	165.6037	165.6037	481.000	481.000
2	91.8048	14.7000	120.000	120.000

TITLE: VERIFY20.ARO

REFERENCE: Mohinder L. Nayyar, Piping Handbook, Sixth Edition, McGraw-Hill, New York, 1992, Page B.343, Example B8.6

GAS: Air

ASSUMPTIONS: 1) Adiabatic flow, 2) Perfect gas

RESULTS:

Parameter	Nayyar	AFT Arrow 2.0
M_1 – Mach number at valve	0.235	0.235
P_1 – Pressure at valve (psia)	661.96	662.56

DISCUSSION:

The problem assumes an unusual inlet boundary condition where the flow rate is known and the stagnation temperature. AFT Arrow uses the static temperature at the inlet because it is typically associated with a flow rate. To match the 120 F stagnation temperature, the inlet static temperature was iterated a few times.

The conditions result in sonic choking at the discharge.

The predictions agree very closely.

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AFT Arrow 2.0 Input
Numatec Hanford Corporation

(1)

12/7/99 12:39 PM

Verify20.aro - Air flow in a pipe, Example B8.6 from Nayyar Page B.343

Mohinder L. Nayyar
Piping Handbook, Sixth Edition, McGraw-Hill, New York, 1992
Page B.343, Example B8.6
Air flow - Example assumes air is a perfect gas and adiabatic flow

See Verify20.doc MS Word file for comparison with published results

Title: Verify20.aro - Air flow in a pipe, Example B8.6 from Nayyar Page B.343

Number Of Pipes= 1
Number Of Junctions= 2

Length March Solution Method with Mach Number Limits
Segments Per Pipe= 10
Mach Number Increment= .01
Pressure Tolerance= .0001 relative change
Mass Flow Rate Tolerance= .0001 relative change
Enthalpy Tolerance= .0001 relative change
Flow Relaxation= .5
Pressure Relaxation= .5

Fluid Database: AFT Standard
Fluid= Air
Max Fluid Temperature Data= 1000 deg. K
Min Fluid Temperature Data= 200 deg. K
Molecular Weight= 28.97 amu
Gas Constant= 0.0685486 Btu/lbm-R
Critical Pressure= 37.25 atm
Critical Temperature= 132.41 deg. K
Acentric Factor= .021
Equation of State= Ideal Gas
Enthalpy Model= Reference
Specific Heat Ratio Accuracy= High
Atmospheric Pressure= 1 atm
Gravitational Acceleration= 1 g's
Standard Pressure= 14.696 psia
Standard Temperature= 60 deg. F
Turbulent Flow Above Reynolds Number= 4000
Laminar Flow Below Reynolds Number= 2300
Specific Heat Ratio Accuracy= High
Atmospheric Pressure= 1 atm
Gravitational Acceleration= 1 g
Standard Pressure= 14.696 psia
Standard Temperature= 60 deg. F
Turbulent Flow Above Reynolds Number= 4000
Laminar Flow Below Reynolds Number= 2300

Pipe Input Table

Pipe	Name	Pipe Defined	Length	Length Units	Hydraulic Diameter	Hydraulic Diam. Units	Roughness	Roughness Units	Losses (K)	Initial Flow
1	Pipe	Yes	90	feet	2.067	inches	0.019	Explicit f	0	

Pipe	Initial Flow Units	Junctions (Up,Down)	Geometry	Material	Size	Type	Special Condition
1		1, 2	Cylindrical Pipe	Steel	2 inch	schedule 40	None

Assigned Flow Table

AFT Arrow 2.0 Input
Numatec Hanford Corporation

(2)

12/7/99 12:39 PM

Verify20.aro - Air flow in a pipe, Example B8.6 from Nayyar Page B.343

Assigned Flow	Name	Object Defined	Database Source	Special Condition	Fluid	Type	Flow	Flow Units	Temperature	Temperature Units
1	Assigned Flow	Yes		None	Air	Inflow	72000	lbm/hr	113.75	deg. F

Assigned Flow	Loss Model
1	0

Tank Table

Tank	Name	Object Defined	Database Source	Special Condition	Fluid	Pressure	Pressure Units	Temperature	Temperature Units	Balance Energy
2	Tank	Yes		N/A	Air	14.7	psia	120	deg. F	No

Tank	Balance Concentration	(Pipe #1) K In, K Out	(Pipe #2) K In, K Out	(Pipe #3) K In, K Out	(Pipe #4) K In, K Out	(Pipe #5) K In, K Out	(Pipe #6) K In, K Out	(Pipe #7) K In, K Out	(Pipe #8) K In, K Out
2	No	(1) 0, 0							

Tank	(Pipe #9) K In, K Out	(Pipe #10) K In, K Out
2		

AFT Arrow 2.0 Output
Numatec Hanford Corporation

(1)

12/7/99

Verify20.aro - Air flow in a pipe, Example B8.6 from Nayyar Page B.343

Mohinder L. Nayyar
Piping Handbook, Sixth Edition, McGraw-Hill, New York, 1992
Page B.343, Example B8.6
Air flow - Example assumes air is a perfect gas and adiabatic flow

See Verify20.doc MS Word file for comparison with published results

Title: Verify20.aro - Air flow in a pipe, Example B8.6 from Nayyar Page B.343
Analysis run on: 12/7/99 12:37:36 PM
Input File: C:\AFT Products\AFT Arrow\Verification\verify20.aro

Execution Time= 2.74 seconds
Total Number Of Pressure Iterations= 0
Total Number Of Flow Iterations= 2
Total Number Of Enthalpy Iterations= 2
Number Of Pipes= 1
Number Of Junctions= 2

Length March Solution Method with Mach Number Limits
Segments Per Pipe= 10
Mach Number Increment= .01
Pressure Tolerance= .0001 relative change
Mass Flow Rate Tolerance= .0001 relative change
Enthalpy Tolerance= .0001 relative change
Flow Relaxation= .5
Pressure Relaxation= .5

Fluid Database: AFT Standard
Fluid= Air
Max Fluid Temperature Data= 1000 deg. K
Min Fluid Temperature Data= 200 deg. K
Molecular Weight= 28.97 amu
Gas Constant= 0.0685486 Btu/lbm-R
Critical Pressure= 37.25 atm
Critical Temperature= 132.41 deg. K
Acentric Factor= .021
Equation of State= Ideal Gas
Enthalpy Model= Reference
Specific Heat Ratio Accuracy= High
Atmospheric Pressure= 1 atm
Gravitational Acceleration= 1 g's
Standard Pressure= 14.696 psia
Standard Temperature= 60 deg. F
Turbulent Flow Above Reynolds Number= 4000
Laminar Flow Below Reynolds Number= 2300
Specific Heat Ratio Accuracy= High
Atmospheric Pressure= 1 atm
Gravitational Acceleration= 1 g
Standard Pressure= 14.696 psia
Standard Temperature= 60 deg. F
Turbulent Flow Above Reynolds Number= 4000
Laminar Flow Below Reynolds Number= 2300
Overall Delta Pressure = -673.699 psia
Total Inflow= 20.0000 lbm/sec
Total Outflow= 20.0000 lbm/sec
Total Energy Inflow= 4149.70 Btu/s
Total Energy Outflow= 4149.70 Btu/s
Total Heat Transferred Into System= 0.00000 Btu/s

Maximum Pressure is 662.559 psia at Junction 1 Inlet
Minimum Pressure is 14.7000 psia at Junction 2 Outlet
Maximum Static Temperature is 120.000 deg. F at Junction 2 Inlet
Minimum Static Temperature is 119.955 deg. F at Junction 1 Inlet

Sonic Choking Exists at Junction 2 (Tank)

Pipe Output Table

AFT Arrow 2.0 Output
Numatec Hanford Corporation

(2)

12/7/99

Verify20.aro - Air flow in a pipe, Example B8.6 from Nayyar Page B.343

Pipe	Mass Flow (lbm/hr)	Vel. In (feet/sec)	Vel. Out (feet/sec)	Mach # In	Mach # Out	P Static In (psia)	P Static Out (psia)	T Static In (deg. F)	T Static Out (deg. F)	T Stag. In (deg. F)	T Stag. Out (deg. F)
1	72,000.0	275.155	1062.54	0.235138	0.984739	662.563	145.708	113.750	27.2966	119.955	120.105

All Junction Table

Jct	P Static In (psia)	P Static Out (psia)	T Static In (deg. F)	T Static Out (deg. F)
1	662.559	662.5590	113.750	113.750
2	270.384	14.7000	120.000	120.000

TITLE: VERIFY21.ARO

REFERENCE: Mohinder L. Nayyar, Piping Handbook, Sixth Edition, McGraw-Hill, New York, 1992, Page B.343-344, Example B8.7

GAS: Air

ASSUMPTIONS: 1) Adiabatic flow, 2) Perfect gas

RESULTS:

Parameter	Nayyar	AFT Arrow 2.0
M_1 – Mach number at valve	0.4096	0.4142
P_1 – Pressure at valve (psia)	25.15	24.95

DISCUSSION:

The problem assumes an unusual inlet boundary condition where the flow rate is known and the stagnation temperature. AFT Arrow uses the static temperature at the inlet because it is typically associated with a flow rate. To match the 120 F stagnation temperature, the inlet static temperature was iterated a few times.

The result is sub-sonic conditions at the discharge.

The predictions agree very closely.

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AFT Arrow 2.0 Input
Numatec Hanford Corporation

(1)

12/7/99 12:41 PM

Verify21.aro - Air flow in a pipe, Example B8.7 from Nayyar Page B.343-344

Mohinder L. Nayyar
Piping Handbook, Sixth Edition, McGraw-Hill, New York, 1992
Page B.343-344, Example B8.7
Air flow - Example assumes air is a perfect gas and adiabatic flow

See Verify21.doc MS Word file for comparison with published results

Title: Verify21.aro - Air flow in a pipe, Example B8.7 from Nayyar Page B.343-344

Number Of Pipes= 1
Number Of Junctions= 2

Length March Solution Method with Mach Number Limits
Segments Per Pipe= 10
Mach Number Increment= .01
Pressure Tolerance= .0001 relative change
Mass Flow Rate Tolerance= .0001 relative change
Enthalpy Tolerance= .0001 relative change
Flow Relaxation= .5
Pressure Relaxation= .5

Fluid Database: AFT Standard
Fluid= Air
Max Fluid Temperature Data= 1000 deg. K
Min Fluid Temperature Data= 200 deg. K
Molecular Weight= 28.97 amu
Gas Constant= 0.0685486 Btu/lbm-R
Critical Pressure= 37.25 atm
Critical Temperature= 132.41 deg. K
Acentric Factor= .021
Equation of State= Ideal Gas
Enthalpy Model= Reference
Specific Heat Ratio Accuracy= High
Atmospheric Pressure= 1 atm
Gravitational Acceleration= 1 g's
Standard Pressure= 14.696 psia
Standard Temperature= 60 deg. F
Turbulent Flow Above Reynolds Number= 4000
Laminar Flow Below Reynolds Number= 2300
Specific Heat Ratio Accuracy= High
Atmospheric Pressure= 1 atm
Gravitational Acceleration= 1 g
Standard Pressure= 14.696 psia
Standard Temperature= 60 deg. F
Turbulent Flow Above Reynolds Number= 4000
Laminar Flow Below Reynolds Number= 2300

Pipe Input Table

Pipe	Name	Pipe Defined	Length	Length Units	Hydraulic Diameter	Hydraulic Diam. Units	Roughness	Roughness Units	Losses (K)	Initial Flow
1	Pipe	Yes	90	feet	7.981	inches	0.014	Explicit f	0	

Pipe	Initial Flow Units	Junctions (Up,Down)	Geometry	Material	Size	Type	Special Condition
1		1, 2	Cylindrical Pipe	Steel	8 inch	schedule 40	None

Assigned Flow Table

AFT Arrow 2.0 Input
Numatec Hanford Corporation

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12/7/99 12:41 PM

Verify21.aro - Air flow in a pipe, Example B8.7 from Nayyar Page B.343-344

Assigned Flow	Name	Object Defined	Database Source	Special Condition	Fluid	Type	Flow	Flow Units	Temperature	Temperature Units
1	Assigned Flow	Yes		None	Air	Inflow	72000	lbm/hr	101	deg. F

Assigned Flow	Loss Model
1	0

Tank Table

Tank	Name	Object Defined	Database Source	Special Condition	Fluid	Pressure	Pressure Units	Temperature	Temperature Units	Balance Energy
2	Tank	Yes		N/A	Air	14.7	psia	120	deg. F	No

Tank	Balance Concentration	(Pipe #1) K In, K Out	(Pipe #2) K In, K Out	(Pipe #3) K In, K Out	(Pipe #4) K In, K Out	(Pipe #5) K In, K Out	(Pipe #6) K In, K Out	(Pipe #7) K In, K Out	(Pipe #8) K In, K Out
2	No	(1) 1, 1							

Tank	(Pipe #9) K In, K Out	(Pipe #10) K In, K Out
2		

AFT Arrow 2.0 Output
Numatec Hanford Corporation

(1)

12/7/99

Verify21.aro - Air flow in a pipe, Example B8.7 from Nayyar Page B.343-344

Mohinder L. Nayyar
Piping Handbook, Sixth Edition, McGraw-Hill, New York, 1992
Page B.343-344, Example B8.7
Air flow - Example assumes air is a perfect gas and adiabatic flow

See Verify21.doc MS Word file for comparison with published results

Title: Verify21.aro - Air flow in a pipe, Example B8.7 from Nayyar Page B.343-344
Analysis run on: 12/7/99 12:41:15 PM
Input File: C:\AFT Products\AFT Arrow\Verification\verify21.aro

Execution Time= 0.99 seconds
Total Number Of Pressure Iterations= 0
Total Number Of Flow Iterations= 2
Total Number Of Enthalpy Iterations= 2
Number Of Pipes= 1
Number Of Junctions= 2

Length March Solution Method with Mach Number Limits
Segments Per Pipe= 10
Mach Number Increment= .01
Pressure Tolerance= .0001 relative change
Mass Flow Rate Tolerance= .0001 relative change
Enthalpy Tolerance= .0001 relative change
Flow Relaxation= .5
Pressure Relaxation= .5

Fluid Database: AFT Standard
Fluid= Air
Max Fluid Temperature Data= 1000 deg. K
Min Fluid Temperature Data= 200 deg. K
Molecular Weight= 28.97 amu
Gas Constant= 0.0685486 Btu/lbm-R
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Gravitational Acceleration= 1 g's
Standard Pressure= 14.696 psia
Standard Temperature= 60 deg. F
Turbulent Flow Above Reynolds Number= 4000
Laminar Flow Below Reynolds Number= 2300
Specific Heat Ratio Accuracy= High
Atmospheric Pressure= 1 atm
Gravitational Acceleration= 1 g
Standard Pressure= 14.696 psia
Standard Temperature= 60 deg. F
Turbulent Flow Above Reynolds Number= 4000
Laminar Flow Below Reynolds Number= 2300
Overall Delta Pressure = -13.3543 psia
Total Inflow= 20.0000 lbm/sec
Total Outflow= 20.0000 lbm/sec
Total Energy Inflow= 4149.09 Btu/s
Total Energy Outflow= 4149.09 Btu/s
Total Heat Transferred Into System= 0.00000 Btu/s

Maximum Pressure is 24.9467 psia at Junction 1 Inlet
Minimum Pressure is 14.7000 psia at Junction 2 Outlet
Maximum Static Temperature is 120.000 deg. F at Junction 2 Inlet
Minimum Static Temperature is 119.834 deg. F at Junction 1 Inlet

Pipe Output Table

AFT Arrow 2.0 Output
Numatec Hanford Corporation

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12/7/99

Verify21.aro - Air flow in a pipe, Example B8.7 from Nayyar Page B.343-344

Pipe	Mass Flow (lbm/hr)	Vel. In (feet/sec)	Vel. Out (feet/sec)	Mach # In	Mach # Out	P Static In (psia)	P Static Out (psia)	T Static In (deg. F)	T Static Out (deg. F)	T Stag. In (deg. F)	T Stag. Out (deg. F)
1	72,000.0	479.282	800.696	0.414173	0.713575	24.9468	14.0338	101.000	67.2485	119.834	119.877

All Junction Table

Jct	P Static In (psia)	P Static Out (psia)	T Static In (deg. F)	T Static Out (deg. F)
1	24.9467	24.9467	101.000	101.000
2	19.6747	14.7000	120.000	120.000

[illegible]