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ACCELERATOR-PRODUCTION-OF-TRITIUM TARGET

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FLOW DISTRIBUTION IN THE ACCELERATOR-PRODUCTION-OF-TRITIUM TARGET

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ABSTRACT

Achieving nearly uniform flow distributions in the accelerator production of tritium (APT) target structures is an important design objective. Manifold effects tend to cause a nonuniform distribution in flow systems of this type, although nearly even distribution can be achieved. A program of hydraulic experiments is underway to provide a database for validation of calculational methodologies that may be used for analyzing this problem and to evaluate the approach with the most promise for achieving a nearly even flow distribution.

Data from the initial three tests are compared to predictions made using four calculational methods. The data show that optimizing the ratio of the supply-to-return-manifold areas can produce an almost even flow distribution in the APT ladder assemblies. The calculations compare well with the data for ratios of the supply-to-return-manifold areas spanning the optimum value. Thus, the results to date show that a nearly uniform flow distribution can be achieved by carefully sizing the supply and return manifolds and that the calculational methods available are adequate for predicting the distributions through a range of conditions.

1. INTRODUCTION

The accelerator-production-of-tritium (APT) target design consists of a series of ladder-like structures (referred to as ladders) positioned vertically in the proton beam, as shown in Fig. 1. The tungsten targets are located in the rungs. Coolant in each ladder

Fig. 1 Schematic of the tungsten neutron source for the 1700-MeV beam design.

flows downward through one leg. From there it is distributed among the various rungs. Flow is horizontal through the rungs and then upward in the other leg.

The power deposition in a given ladder is nearly uniform among the various rungs. Thus, it is important to establish a nearly uniform flow distribution among the rungs. This distribution can be achieved by using an optimized downcomer-to-riser-area ratio (~ 0.7) and by increasing the flow resistance across the rungs to the extent practical.

One leg of each ladder serves as the supply manifold for entering coolant and the other leg as the return manifold for exiting coolant. Flow on the inlet side is downward; flow in the exit manifold is upward. This configuration is sometimes called a "reverse flow manifold system" in the literature. The ladders show the flow distribution phenomena characteristic of coupled supply and return manifolds with a relatively small length-to-diameter ratio. In the supply manifold, the fluid traveling down the manifold decelerates as fluid is drawn off through each of the branches. Pressure recovery occurs as a consequence of the deceleration of the fluid remaining in the leg. Losses act to limit the pressure recovery. The pressure recovery causes the pressure to be highest at the end

furthest from the fluid inlet, at the bottom. In the discharge manifold, the pressure gradient must be sufficient to accelerate the fluid and overcome all losses. Thus, the pressure drops in the direction of the flow. The maximum pressure in the discharge manifold is at the end furthest from the outlet, at the bottom. Both manifolds are sufficiently short so that frictional pressure drop is small compared to the pressure recovery effect.

In APT, the branches have been called "rungs"; in literature, the branches are sometimes referred to as the "laterals." The power deposition in a given ladder is nearly uniform among the various rungs. Thus, it is best to have equal flow rates in all of the rungs. This is the classical problem of manifold flow design. To have equal flow rates in the rungs of a ladder, we need to have approximately equal pressure differences between the two ends of the rungs. Normalized by the dynamic pressure in the manifolds, the magnitude of the losses caused by dividing flows is smaller than the magnitude of the losses associated with mixing flow streams. However, we can approximately equalize the losses in the two manifolds by having a smaller dynamic pressure in the discharge manifold than in the supply manifold. We do this by making the cross-sectional area of the discharge manifold appropriately larger than that of the supply manifold.

There are several ways to produce a more even flow distribution. As stated in the previous paragraph, appropriately increasing the size of the discharge manifold relative to the supply manifold is an effective method. Increasing the size of both manifolds also improves the rung-to-rung flow distribution. Increasing the flow resistance of the branches to the maximum extent practical also acts to even the flow distribution. Using these approaches, the maximum deviation in branch flow from the average branch flow can be reduced from ~20% to ~1%. The methods evaluated for predicting the flow distribution show somewhat different flow distributions and slightly different optimum ratios of the supply-to-return-manifold flow areas, although the trends predicted are similar. This is illustrated by Fig. 2, which shows the maximum fractional deviation in rung flows predicted by two codes for the APT ladder with the highest power density. Thus, system-specific data are needed to determine which methods provide the best answers and also to evaluate the best values for the empirical constants used in some of these methods.

The problem of determining and optimizing flow distributions in various manifold arrangements has been the subject of many papers. Early papers looked mainly at systems that can be characterized as distribution manifolds, such as gas burners (Keller, 1949). McNown (1954) understood that manifolds with discrete branch points spaced a sufficient distance apart can be analyzed using data from single junctions (tees) with fully developed flow. There is a significant body of work on junction flow losses that supports this type of manifold analysis. Miller (1971) analyzed most of the junction data available through the time of his work. McNown (1954) also showed that tees spaced closely enough that fully developed flows cannot reestablish between branch points exhibit

different loss characteristics than tees with fully developed flows. The use of different supply- and return-manifold sizes to achieve a nearly uniform flow distribution is discussed by Kreith (1990).

Idelchik (1994) showed that a circulation forms in the main pipe downstream of a dividing junction on the side of the pipe away from the junction and that the velocity profile is skewed toward the wall with the junction. Downstream of combining tees, the velocity profile is skewed toward the side of the pipe away from the junction. This reference provides loss coefficients for several tee and wye configurations, as well as hydraulic resistance information for a variety of other components.

Many authors have derived and solved nonlinear ordinary differential equations (ODEs) for flow through manifolds with a continuous discharge or combining flow. Discrete branching problems can be approximated with these methods by averaging the branch area over the length of the pipe. Haerter (1963) developed this approach where the deviation from branching losses for fully developed flow was accounted for with an empirically determined "recovery coefficient." His work was directed toward ventilation systems such as those used in long highway tunnels, including both supply and return ducts. Bajura (1971), Bajura and Jones (1976), and Pigford et al. (1983) are among the researchers using an ODE to analyze manifold problems. These approaches require two empirical coefficients. The coefficients used by Bajura and Jones (1976) and Pigford et al. (1983) differ by a factor of 2, and thus, the constants for these approaches easily can be related. Pigford et al. (1983) evaluated these empirical constants from data for single tees. As discussed previously, the use of fully developed flow tee data for manifold problems

Fig. 2 Calculations showing maximum fractional deviation in rung flows from average rung flow as a function of the ratio of the supply-to-return-manifold areas.

has inaccuracies if the branch points are spaced closely enough that flow between branches is not fully developed. Bajura and Jones (1976) developed their approach to work for dividing-flow, combining-flow, reverse-flow, and parallel-flow manifold systems. Riggs (1987) developed an algebraic design equation from the ODE approach of Bajura and Jones (1976). Riggs (1987) also evaluated the empirical coefficients given by Pigford et al. (1983) and Bajura and Jones (1976).

The literature does not provide sufficient information to evaluate the errors involved in using one-dimensional (1D) approaches with branch spacings that are too close together to allow flow to become fully developed between branches. The empirical coefficients for the ODE approaches are given as a range of values. Thus, experimental data are needed for an accurate determination of the flow characteristics of a particular manifold system.

An experimental rig, similar in configuration to an APT ladder, was designed to obtain flow and pressure distribution data over a range of supply-to-return-manifold sizes. The sizes can be varied with "inserts" that slide into either of the manifolds. The supply-to-return-manifold diameters cover the range that may be used in this project. The rungs in the test rig use orifice plates to model the flow resistance of the tungsten targets. The 28 rungs in the test rig correspond to the number of rungs in the current design for the ladder with the highest power density.

Four methods are being evaluated for use in analyzing ladder flow distributions. The Transient Reactor Analysis Code (TRAC) was developed by Los Alamos National Laboratory for the analysis of water-cooled reactor transients. It can model a 1D piping system and has many other capabilities. TRAC solves a finite difference approximation to the equations of motion. Fathom [Applied Flow Technology (1998)] is a nodal code for the solution of piping networks. Tee losses in Fathom are based on Idelchik (1994). The ODE approach of Bajura and Jones (1976), with coefficient terms for reverse manifold systems as given by Riggs (1987), also has been used. The fourth method involves a code written especially for this problem and uses tee loss coefficients from Idelchik (1994). The advantage of this method is that corrections to the loss coefficients can be made easily. Provision for laminar and transition flows also has been made in this code.

Comparisons between data and calculations show that all of the calculational methods used will calculate the flow distribution well, with calculated rung flow divided by average rung flow, within a few percent of the data.

2. EXPERIMENTAL PROGRAM

The test rig consists of an APT ladder model with 28 rungs in a test loop capable of driving greater-than-nominal flows. Orifice plates in each of the rungs are used to provide a near-nominal flow resistance through the rungs. By replacing the orifice plates,

the effect of the flow resistance over a wide range of flow rates can be investigated parametrically. The diameter of the supply and return manifolds can be changed with machined inserts. Differential pressure measurements are made across each of the rung orifice plates. Pressure measurements are made at the top, midpoint, and bottom of the supply and return manifolds. An overall flow measurement and temperature measurements also are made. An experimental program is underway to provide a database for validating calculational methods to determine the configuration that optimizes the rung-to-rung flow distribution.

2.1 Test Apparatus

The test assembly consists of a supply and return manifold with 28 rungs (laterals) between them (Fig. 3). This assembly is made of acrylic pipe. The nominal inner diameter (i.d.) of the inlet and exit manifolds is 0.1143 m (4.5 in.). The rungs have an i.d. of 0.03175 m (1.25 in.), are 0.3937 m (15.5 in.) long, and are spaced 0.0635 m (2.5 in.) center to center. A flanged joint is located in each rung to hold an orifice plate. These joints are staggered from rung to rung to allow a closer spacing between rungs. The tests presented in this paper were performed with 0.01671-m (0.658-in.)-diam orifice plates. Inserts that reduce the i.d. of either the supply or return manifolds have been machined with i.d.s of 0.0889 m (3.5 in.), 0.09525 m (3.75 in.), and 0.1016 m (4.0 in.). Figure 4 shows the inserts schematically. Ten different combinations will be tested. The initial three tests are presented in this paper.

The test loop has three 25-hp pumps plumbed in parallel, each capable of flow rates of 600 gpm at low-head losses. The test loop has been built from PVC piping with vibration isolators at the exit of each pump. The entire loop can be pressurized to 20 psig at the tank to ensure that there is no cavitation at the orifice plates during a test.

Because measuring the differential pressure across all 28 rungs simultaneously would involve a prohibitive number of expensive transducers, the instrumentation was designed so that quick connects could be used to move five of the six differential pressure transducers available to different rungs easily and quickly. The sixth transducer was left on the top rung to ensure that changes in flow conditions during a test could be identified. The data acquisition system consisted of a Hewlett Packard 3852A Data Acquisition/Control Unit and a Macintosh PowerPC running LabVIEW 2.2 software. All of the pressure transducers and thermocouples were calibrated for this experiment. Approximately 30 steady-state readings were taken for each rung and the average value reported. The uncertainty of the measurements was evaluated by considering the instrument accuracy and data scatter. The pressure transducer uncertainty was within 1% of the reading. The conversion of a pressure reading to flow rate was performed by calibrating the pressure drop vs flow rate for a single orifice. The uncertainty of the pressure drop-to-flow rate conversion was 2% of the reading.

Fig. 3. Schematic of the test rig.

Fig. 4. Schematic of the inserts.

2.2 Test Procedure

The independent variables for these tests are the downcomer and riser diameter, the orifice inside diameter, and the total ladder flow rate. Testing will be performed from ~400 to 1200 gpm in 100-gpm increments for each configuration. Calibration tests also have been run for single orifices. When this paper was written, the test program had begun with only three configurations tested. Table 1 shows the configurations tested to date.

3. COMPARISONS BETWEEN DATA AND CALCULATIONS

Four calculational methods are being evaluated for use in analyzing APT ladder flow problems. The tests to date include tests with the ratio of the supply- to return-manifold areas greater than, less than, and near the optimum value. The optimum is the area ratio that gives a flow distribution that is nearly uniform through all of the rungs.

3.1 Calculational Methods

TRAC is a large code that was developed at Los Alamos National Laboratory (Spore et al., 1992) for the United States Nuclear Regulatory Commission to analyze transients in water-cooled reactors and related facilities. Features relevant to this problem include a 1D finite difference piping network analysis capability and, for the actual target, heated-structure-to-fluid coupling and two-phase flow and boiling heat-transfer capabilities. TRAC has been assessed extensively against numerous experiments. The TRAC models use tee and pipe components to represent the piping and junctions in the target ladders.

Fathom [Applied Flow Technology (1998)] is a commercial piping network code capable of single-phase steady-state analyses. It uses a nodal approach to solve piping networks. Junction losses use the hydraulic loss coefficients from Idelchik (1994). The Fathom model for the ladder utilizes tee and pipe components.

Table 1. Configurations for initial tests.

Supply Manifold Inner Diameter	Return Manifold Inner Diameter	Ratio of Supply-to Return- Manifold Areas	Orifice Size
0.1143 m (4.5 in.)	0.1143 m (4.5 in.)	1.0	0.01671 m (0.658 in.)
0.0889 m (3.5 in.)	0.1143 m (4.5 in.)	0.605	0.01671 m (0.658 in.)
0.09525 m (3.75 in.)	0.1143 m (4.5 in.)	0.694	0.01671 m (0.658 in.)

The ODE method of Bajura and Jones (1976) was used with the coefficients for a reverse flow manifold system tabulated by Riggs (1987). This method requires two empirical constants. These were evaluated from the test data for the test configurations with ratios of the supply-to-return-manifold areas at the largest and smallest values tested.

Finally, a FORTRAN program, which was written specifically for analyzing this problem, uses a nodal approach with loss coefficients from Idelchik (1994). Some of the loss coefficient equations used in this code differ from the equations used in Fathom because Idelchik (1994) sometimes has multiple correlations applicable to a particular condition. This approach offers the advantage that loss coefficients for transition and laminar flows can be adjusted as necessary. This code also offers the advantage that loss coefficients may be modified to account for the multidimensional nature of the flow in the supply and return manifolds. In addition, this approach allows us to include Reynolds number dependencies of loss coefficients to model laminar and transition flows.

3.2 Experimental Results and Comparisons to Calculations

The experimental program was still in progress when this paper was written. The results presented here were the first three runs of the test program. These include tests with the supply-to-return-manifold area ratios of 1.0, 0.605, and 0.694. These values are respectively greater than, less than, and nearly equal to the optimum ratio.

Figure 5 shows the rung flow distribution obtained with both the supply and return manifolds having an i.d. of 0.1143 m (4.5 in.) and a near-nominal flow rate. The layout of the following plots was selected to correspond to the physical ladder layout to illustrate better the spatial distributions that occur. The distribution in Fig. 5 is characteristic of cases with the supply and return manifolds having the same diameter. The distribution is skewed toward the higher rungs. Calculations show that decreasing the supply- and return-manifold diameters to 0.0889 m (3.5 in.) increases the deviation between maximum and average rungs by an additional ~10%. The comparison with calculated values shows a reasonable comparison for all of the methods.

Figure 6 shows the rung flow distribution with the supply manifold having an i.d. of 0.0889 m (3.5 in.) and the return manifold with an i.d. of 0.1143 m (4.5 in.) and near-nominal flow rate. This time, the distribution is skewed toward the bottom rungs. This is characteristic of cases with the area ratio less than optimum. Again, all of the calculations compare reasonably well, although some are better than others. The insert produced an abrupt area change above the first rung in the supply manifold without adequate length for flow to become fully developed. Extensions are being prepared for the inserts to provide a longer entrance length. These extensions were not available when this test was run, and the large difference between flows for rungs 1 and 2 may be at least partly attributed to this. Because flow is likely to be fully developed only for the inlet to rung 1,

rung 1 may exhibit flow characteristics that differ slightly from the other rungs. This will be investigated in future tests.

Figure 7 shows the rung flow distribution with a supply manifold i.d. of 0.09525 m (3.75 in.) and return manifold i.d. of 0.1143 m (4.5 in.). The flow rate is near the nominal flow rate. The area ratio is 0.694, which is close to the optimum ratio. The maximum deviation of the rung flow from the average rung flow is ~1%, which is within the experimental error of the facility. The TRAC calculation gives the best agreement, within ~1% of the data, although all of the calculational methods do reasonably well.

Based on the current assessment, 1D models are quite adequate in assessing the flow distribution within a given ladder. Experimental and analytical studies continue to extend this conclusion to a wider range of flow rates and rung resistances.

4. CONCLUSIONS

Designing the APT target ladders to produce a uniform flow distribution through the target assemblies is an objective that is being pursued through a combined experimental and analytical program. Hydraulic experiments are underway to provide a database for validating calculational methods and to help develop a fundamental understanding of the phenomena involved. The results to date show that (1) a nearly uniform flow distribution can be achieved by carefully sizing the supply and return manifolds and (2) the calculational methods available are adequate for predicting the distributions through a range of conditions.

Fig. 5a. Comparison of data to TRAC calculation for 0.1143-m (4.5-in.)-i.d. supply and return manifolds for a flow rate of $0.07455 \text{ m}^3/\text{s}$ (1181.7 gpm).

Fig. 5b. Comparison of data to Fathom calculation for 0.1143-m (4.5-in.)-i.d. supply and return manifolds for a flow rate of $0.07455 \text{ m}^3/\text{s}$ (1181.7 gpm).

Fig. 5c. Comparison of data to Bajura equation for 0.1143-m (4.5-in.)-i.d. supply and return manifolds for a flow rate of $0.07455 \text{ m}^3/\text{s}$ (1181.7 gpm).

Fig. 5d. Comparison of data to Ladder code calculation for 0.1143-m (4.5-in.)-i.d. supply and return manifolds for a flow rate of $0.07455 \text{ m}^3/\text{s}$ (1181.7 gpm).

Fig. 6a. Comparison of data to TRAC calculation for 0.0889-m (3.5-in.)-i.d. supply manifold and 0.1143-m (4.5-in.)-i.d. return manifolds for a flow rate of $0.07244 \text{ m}^3/\text{s}$ (1148.2 gpm).

Fig. 6b. Comparison of data to Fathom calculation for 0.0889-m (3.5-in.)-i.d. supply manifold and 0.1143-m (4.5-in.)-i.d. return manifolds for a flow rate of $0.07244 \text{ m}^3/\text{s}$ (1148.2 gpm).

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Fig. 6d. Comparison of data to Ladder code calculation for 0.0889-m (3.5-in.)- i.d. supply manifold and 0.1143-m (4.5-in.)-i.d. return manifolds for a flow rate of $0.07244 \text{ m}^3/\text{s}$ (1148.2 gpm).

Fig. 7a. Comparison of data to TRAC calculation for 0.09525-m (3.75-in.)-i.d. supply manifold and 0.1143-m (4.5-in.)-i.d. return manifolds for a flow rate of $0.06941 \text{ m}^3/\text{s}$ (1100.1 gpm).

Fig. 7b. Comparison of data to Fathom calculation for 0.09525-m (3.75-in.)-i.d. supply manifold and 0.1143-m (4.5-in.)-i.d. return manifolds for a flow rate of $0.06941 \text{ m}^3/\text{s}$ (1100.1 gpm).

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