Title: Two-phase flow studies

FINAL REPORT

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Brown University

Providence, Rhode Island 02912

J. Kestin, Principal Investigator

P.F. Maeder, Co-Principal Investigator

MASTER

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INTRODUCTION.

This is the Final Report for DOE contract DE-AC02-79ET27225.M001 to Brown University for the period June 1, 1979 to August 31, 1980. The principal investigator was Dr. J. Kestin, the co-principal investigator was Dr. P. F. Maeder, and the technical staff was comprised of: Dr. R. DiPippo, Dr. Z. Bilicki, Dr. H.E. Khalifa, Dr. R.A. Dobbins, Dr. E.E. Michaelides, Mr. D.A. Dickinson, Mr. M. Delor and Mr. H. Olia.

The original proposal was intended for a period of two years. It was decided to terminate the present contract after one year, and to write a new two-year contract that will cover essentially the second year of the original proposal plus additional tasks. Furthermore, there were changes in program emphasis during the course of this contract as a result of consultation with and recommendations by DOE program managers. The following report covers the first year of the proposal with modifications to the program as approved by the DOE.

A. CRITICAL SURVEY OF LITERATURE

This task has been completed for the subject of two-phase (liquid-gas) flow. The report has been issued as a Brown University report: "Geothermal Two-Phase Flow: A Selective, Annotated Guide to the Literature", Z. Bilicki, R. DiPippo, E.E. Michaelides, J. Kestin and P.F. Maeder, Rep. No. GEOFLO/7, DOE/ET/27225-11, June 1980, Brown University, Providence, RI.

B. DESIGN OF TWO-PHASE FLOW TESTING FACILITY

1. Design Objectives

The facility will be suitable for the detailed flow testing of substances in two-phase flow in pipes of diameter up to 2 inch. Flow conditions to be achieved are to be from pure liquid to fully-choked two-phase flow with and without the addition or rejection of heat in the test section.

Since the power requirements for a continuous flow facility of this type are rather large, we decided to design an intermittent facility which will store power in an accumulator-booster on the high pressure side and in a large mass of methanol on the low-pressure low-temperature side. The only other large piece of equipment that is required is a condenser; pumping equipment is of moderate size and the refrigeration equipment is of a size that can be easily managed.

After investigating a great number of different substances it was decided to run the facility first with R-114; however, other liquids can be substituted. Figure A1 and the attached legend illustrate schematically the proposed installation.

The test section can be arranged either to be vertical, thus permitting to investigate the influence of gravity, or horizontal. The test section design will be flexible and suited to a particular set of experiments to be performed. It is expected that several test sections will be built, each fitting interchangeably and easily into place.

2. Operation of Facility

The main components of the apparatus are the booster, A, hot-accumulator combination, B, test section (with instrumentation), F, F', condenser, C, cold-accumulator, E, and the dump tank, D. Auxiliary

Fig. A1. Schematic of proposed testing facility.

equipment includes the electric heaters, refrigeration and distribution systems and the various safety and control devices.

The test fluid flows from the hot accumulator B as a saturated liquid. Two-phase flow is developed in the test section F(F') by an adjustable throttle and the pressure loss in the section itself. As fluid leaves the test section it is converted to saturated liquid in the condenser using a methanol-water mixture, stored in the cold accumulator E, as coolant. The condensed fluid then enters the dump tank D.

The flow through the test section F (or F') is driven by the difference in pressure between the hot accumulator B and the dump tank D. The booster contains vapor which is allowed to enter the hot accumulator through a pressure reducing valve, allowing the pressure in the latter container to be maintained constant as the liquid leaves it. The pressure in the dump tank is low enough to cause the flow in the test section to be choked while measurements are taken. Thus, the latter will occur in a steady-state flow condition.

With the apparatus shut down, all fluid is stored in the dump tank, with its equilibrium vapor filling the rest of the system (test section and containers) at room temperature. Preparation for a cycle is started by pumping liquid from the dump tank to the hot accumulator and booster, with both vented to the dump tank. The vents are then closed and the containers are heated electrically to the desired starting conditions. The dump tank is cooled to the desired conditions by circulating the remaining liquid through the condenser. The methanol-water mixture in the cold accumulator is kept cool continuously by the refrigeration system.

After the starting conditions have been attained, the valve upstream of the test section is opened and measurements made when the flow has become steady. Once started, measurements can be made continuously or in short intervals until the pressure difference becomes too low. Alternatively, starting conditions can be re-established after a short interval by the procedure outlined above. The resulting flexibility in operation allows experiments to be performed for a wide variety of conditions without long time delays or difficult equipment changes.

Figures A2 and A3 show the positioning of the elements of the installation in the Prince Laboratory of Brown University.

3. Specification of Major Equipment

<u>Item</u>	<u>Designation</u>	<u>Dimension</u>	<u>ASME rating</u>
1. Booster	A	34.3 ft ³ (30"x84")	240 psig/200°F
2. Hot accumulator	B	34.3 ft ³ (30"x84")	125 psig/650°F
3. Dump Tank	D	34.3 ft ³ (30"x84")	125 psig/650°F
4. Cold accumulator	E	1000 gal (48"x144")	15 psig/-30°F

Items 1-4, quotations received from Massachusetts Engineering Co., Avon, Mass.

5. Condenser	C	1 shell, 8 pass nominal 200 ton - Model 28-14
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Item 5, quotation received from Patterson-Kelley Co., Stroudsburg, PA

Alternate: 3 shells, 3 pass each - Models HC-201
quotation received from York Div., Borg-Warner Corp., York, PA

6. Chiller	Capacity: 32 MBH Power: 7.1 kw - Model IPWL-010
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Item 6, quotation received from Dunham-Bush, Inc., Hartford, CT

<u>Item</u>	<u>Designation</u>	<u>Dimension</u>	<u>ASME rating</u>
7. Chiller Pump	P-1	1/2 h.p./10 gpm	Circulator
8. Condenser Pump	P-2	10 h.p./400 gpm, base mounted	
Items 7, 8, Local Supplier: Taco Inc., Cranston, RI.			
9. Refrigerant Pump	P-3	1/2 h.p./1.5 gpm, Diaphragm	
Item 9, quotation outstanding.			

ASSEMBLY OF TWO-PHASE FLOW TESTING FACILITY
AND COST OF CAPITAL EQUIPMENT

Item	Vessels	Cost \$	Ship \$	Insul. \$	Refrig. Charge \$	Struct. \$	Labor \$	Total \$
a)	Hot accum.	900	25	230	4000	200	250	5605
b)	Booster	1250	25	230	480	200	250	2435
c)	Ref. Reservoir	900	25	230	480	200	250	2085
d)	Cool. Reservoir	1800	50	1000	420	200	250	3720
<u>Other Equipment</u>								
e)	Condenser	21550	200	-	-	200	360	22310
f)	Ref. Pump	250	25	-	-	-	60	335
g)	Cool. Pump	800	-	-	-	-	240	1040
h)	Chiller Pump	400	-	-	-	-	120	520
i)	Chiller	6550	150	-	-	-	360	7060
	Elec. Htrs. (2)	500	-	-	-	-	240	740
	Pipe, valves, fitt.	5000	-	1950	-	-	6480	13430
<u>Controls</u>								
	6" 3-way valve & sensor	600	-	-	-	-	180	780
	Press. Reg. (3)	75	-	-	-	-	50	125
	Elec. Wiring	1500	-	-	-	-	1440	2940
<u>Test Section</u>								
j)	Tubing	110	-	-	-	500	500	1110
	Fittings	100	-	-	-	-	400	500
k)	Flow Metering Eq.	4900	25	-	-	-	-	4925
l)	Press Metering Eq.	12000	25	-	-	-	-	12025
	Flow Control Eq.	200	-	-	-	-	800	1000
Total								82685
Misc.*								16540
GRAND TOTAL \$								99225

*Misc. @ 20%
of Total

* 8% Start/Check Warranty
12% Congingency & Escalation
Detail Design & Drawings

<u>Item</u>	<u>Description</u>	<u>Possible Supplier</u>
a	34.4 ft. ³ (30"x84") ASME Rating 125 psig/650°F	Massachusetts Engineering Company (Avon, MA)
b	34.4 ft. ³ (30"x84") ASME - 240 psig/200°F	Vessels Constructed & Tested to ASME rating
c	34.3 ft. ³ (30"x84") ASME - 125 psig/650°F	" "
d	1000 gal (48"x144") ASME - 15 psig/-30°F	" "
e	1 shell @ nom. 200 ton (8 pass) Model 28-14 Alternate: 3 shells, 3 pass each (Model HC-201)	Patterson-Kelley Co. (Stroudsburg, PA) York Div., Borg-Warner Corp. (York, PA)
f	1/2 h.p./1-1.5 gpm diaphragm type	
g	10 h.p./400 gpm base mounted	Taco Inc. (Cranston, RI)
h	1/2 h.p./10 gpm Circulator	Taco Inc. (Cranston, RI)
i	32 MBH capacity 7.1 KW power required (Model IPWL-010)	Dunham-Bush, Inc. (Hartford, CT)
j	36', Cast Acrylic Transparent @ \$3/ft.	Martin Plastics (Prov., RI)
k	Flow Meter - Coriolis type Model B200F Indicator and Totalizer Model D10RT	Micro Motion Inc. (Boulder, CO)
l	5 Pressure transducers Quartz-Resonator type Model 2200-A Signal processor Model 600	Paroscientific, Inc. (Redmond, WA)
	Liquids-Working Fluid R-114 3100 lb. @ \$1.60/lb. Coolant Methanol 350 gal. @ \$1.20/gal	R.I. Refrigeration Co. (Prov., RI) T.H. Baylis Co. (Warwick, RI)

Fig. A2 Arrangement of Test Facility in Prince Laboratory

ELEVATION

FIRST FLOOR PLAN

Fig. A3 Arrangement of Test Facility
in Prince Laboratory

BASEMENT PLAN

C.. DESIGN OF NOZZLE LOOP

The design of a test facility incorporating a convergent-divergent nozzle to determine the Wilson line for a series of potential binary-cycle working fluids has been omitted following discussions with the program manager. In future work to be supported by DOE, it remains to be decided whether the problems associated with retrograde condensation in turbines and expanders are sufficiently severe to warrant a full experimental study.

D. THERMOPHYSICAL PROPERTIES

The expertise of the Brown group in the area of thermophysical properties, both theoretical and experimental, was brought to bear on the problem of secondary working fluids for binary plants, in general, and of isobutane, in particular. In this connection, J. Kestin has participated in several meetings and given guidance to a program aimed at developing a fundamental formulation of an equation of state for isobutane. A parallel experimental program on the measurement of the properties of aqueous solutions of various salts (i.e., brines) has been continuing at Brown, with funds from other sources.

Our efforts in this area may be summed up by the following listing:

Allied Chemical and Sperry Research. Professor Kestin attended a joint meeting between the staffs of the two institutions in June of 1979. During this meeting the staff of Allied Chemical presented their experimental program for the measurement of the properties of R-114. Suggestions were offered which were subsequently incorporated in the installations. The information transmitted to us is that these suggestions contributed to the success of the experimental program even though the company has not communicated the results of measurement for further verification.

NBS. Several meetings and visits were arranged (Washington, DC in November 1979, Gaithersburg, MD in January 1980 and June 1980, and Boulder, CO in March 1980). During these visits the staffs of DGE and NBS agreed on a program of measurement and calculation of the properties of isobutane and isobutane-isopentane mixtures. During the remaining visits, Professor Kestin inspected the installations and monitored progress. The first contribution, a new and improved formulation of the equilibrium properties of isobutane became available in July 1980.

E. DESIGN MANUAL

Although this aspect of the proposal was envisaged and planned to be carried out during the second year of the program, some work has been done that will constitute an important part of the geofluid transmission system manual. In particular a rigorous study of the flow in geothermal wells has been undertaken, and a series of reports written:

"Flow in Geothermal Wells. Part I. Fundamentals of Two-Phase Flow by the Method of Irreversible Thermodynamics", Z. Bilicki and J. Kestin, Brown University Rep. No. GEOFLO/3, April 1980.

"Flow in Geothermal Wells. Part II. Working Equations for One-Dimensional Flow through a Circular Vertical Channel", Z. Bilicki and J. Kestin, Brown University, Rep. No. GEOFLO/4, April 1980.

"Flow in Geothermal Wells. Part III. Calculation Model for Self-Flowing Well", Z. Bilicki, J. Kestin and E.E. Michaelides, Brown University, Rep. No. GEOFLO/5, April 1980.

"Prediction of the Entropy Production and Pressure Losses in Two-Phase Flow from the Mixing Length Theory", P.F. Maeder and E.E. Michaelides, Brown

University, Rep. No. GEOFLO/2, April 1980.

"Flow in Geothermal Wells. Part IV. Transition Criteria for Two-Phase Flow Patterns. Critical Two-Phase Flow", Z. Bilicki and J. Kestin, Brown University Rep. No. GEOFLO/6, May 1980.

Furthermore, we conducted a week-long seminar on the next steps to be taken in the study of two-phase flow from July 21-25, 1980. Participants included representatives from the Denver Research Institute, Sperry Research Center, General Electric Research Laboratories, and Brown University (regular and visiting faculty plus graduate students). The seminar provided a forum for interaction between academic and industrial/research people working on a common problem. The results have been issued as a Brown Report: "Executive Summary: The Next Steps in Two-Phase Flow", R. DiPippo, Rep. No. GEOFLO/8, DOE/ET/27225-12, July 1980, Brown University, Providence, RI.

F. ADVANCED ENERGY CONVERSION SYSTEMS

The state of the art in geothermal energy conversion has been closely monitored. Developments in the United States and abroad have been studied and several reports written. Work continued in the area of hybrid combustion - geothermal power cycles, and led to the publication of a paper on the subject. Finally, a seminar on geothermal energy conversion fundamentals and applications was conducted at Brown University at the request of, and for certain members of, the Department of Energy.

In detail, our work in this area may be summarized by the following listing:

Report "Compound Hybrid Geothermal-Fossil Power Plants", R. DiPippo and E.M. Avelar, C00/4051-44, Rep. No. CATMEC/31, June 1979.

Trip Report "Geothermal Energy in Iceland", J. Kestin, Brown University, June 16-21, 1979.

- Paper "Impact of Hybrid Combustion-Geothermal Power Plants on the Next Generation of Geothermal Power Systems", R. DiPippo, Proc. Third Annual Geothermal Conf., Electric Power Research Institute, June 25-29, 1979.
- Meeting "DOE-DGE/Japan Geothermal Specialists Meeting", J. Kestin and R. DiPippo, Washington, DC, August 13-14, 1979.
- Paper "Compound Hybrid Geothermal-Fossil Power Plants", R. DiPippo and E.M. Avelar, Geothermal Resources Council, Transactions, Vol. 3, September 1979, pp. 165-168.
- Seminar "Seminar on the Fundamentals of Geothermal Energy Conversion", Barus-Holley Bldg., Brown University, January 4, 1980.
- Paper "Compound Hybrid Geothermal-Fossil Power Plants: Thermodynamic Analyses and Site-Specific Applications", R. DiPippo, E.M. Avelar, J. Kestin and H.E. Khalifa, Energy-sources Technology Conference and Exhibition, Paper No. 80-PET-83, New Orleans, February 3-7, 1980. Also, accepted for publication in ASME Transactions: J. of Engin. for Power.
- Trip Report "Geothermal-Preheat Hybrid Power Plant at Marchwood Engineering Laboratories of the British C.E.G.B.", J. Kestin, Brown University, April 17 and 22, 1980.
- Paper "Worldwide Geothermal Power Plants: Status as of June 1980", R. DiPippo, Fourth EPRI Geothermal Conference and Workshop, Monterey, CA, June 23-26, 1980.
- Paper "Geothermal Power Plants in China", R. DiPippo, Fourth EPRI Geothermal Conference and Workshop, Monterey, CA, June 23-26, 1980.

Paper

"Ahuachapán Geothermal Power Plant, El Salvador", R. DiPippo,
Fourth EPRI Geothermal Conference and Workshop, Monterey, CA,
June 23-26, 1980.