

GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION
SPONSORED PROJECT TERMINATION

Date: June 10, 1980

Project Title: Heat Pipe Startup from the Supercritical State

Project No: E-25-678

Project Director: Dr. Gene T. Colwell

Sponsor: National Science Foundation

Effective Termination Date: 12/31/79

Clearance of Accounting Charges: 12/31/79

Grant/Contract Closeout Actions Remaining:

- ☒ Final Invoice and Closing Documents
- ☒ Final Fiscal Report
- ☒ Final Report of Inventions
- ☐ Govt. Property Inventory & Related Certificate
- ☐ Classified Material Certificate
- ☐ Other _____

Assigned to: M.E. (School/~~Laboratory~~)

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Other C. E. Smith

PROGRESS REPORT

HEAT PIPE STARTUP FROM THE SUPERCRITICAL STATE

a

Progress Report Submitted to

THE NATIONAL SCIENCE FOUNDATION

WASHINGTON, D.C.

by

The School of Mechanical Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332

for the period

July 15, 1977 to July 15, 1978

Grant Number
ENG77-04130

Submitted on October 15, 1978

PROGRESS REPORT SUBMITTED
TO THE NATIONAL SCIENCE FOUNDATION

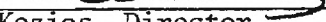
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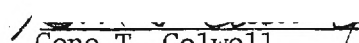
School of Mechanical Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332

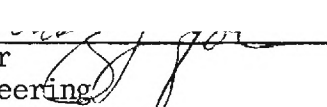
HEAT PIPE STARTUP FROM THE SUPERCRITICAL STATE


Grant Number: ENG77-04130
Period Covered by Progress Report: July 15, 1977 to July 15, 1978
Principal Investigator: Dr. Gene T. Colwell, Professor
Social Security Number: 409-56-8743
Telephone Number: (404) 894-3246

ENDORSEMENTS:


S. P. Kezios, Director
School of Mechanical Engineering


Gene T. Colwell
Principal Investigator


W. M. Sangster
Dean of Engineering


D. L. Allen, Deputy Director
Contract Administration

SUMMARY

The general goals of this project are to gain a better understanding of the transient behavior of heat pipes and to study the transient flow of liquids in Complex Capillary structures. Of particular interest is the examination of heat pipe transient operation near the critical point of the working fluid (both supercritical and subcritical operation) and rewetting of capillary structures after dryout. Both theoretical and experimental approaches are being used in this study and it is hoped that the work will result in information which will be of use in heat pipe design and other areas where capillary action is important.

During the first year of this grant, significant progress has been made. Work has continued on a transient theoretical model and an associated computer program which predicts dependent parametric effects of changes in independent heat pipe parameters which might be made in the course of operating a heat pipe system. The accuracy and usefulness of the model has been improved by incorporating new techniques into the program for storing and using thermophysical data, by improving numerical solution procedures, and by changing the input and output methods employed. Also during the first year of the grant the design, selection, and assembly of test instrumentation has been essentially completed. In addition, the test section has been designed and assembly is well under way. It is expected that initial experimental testing will begin in the fall of 1978 and continue through the winter and spring of 1979.

A Ph.D. candidate has been supported in the first year of the grant. He has now completed almost all the requirements for the degree with the exception of his thesis. During the coming year he will work full time on the project and it is expected that he will receive the degree in December.

of 1979. He is currently working to further improve the theoretical model and the solution techniques which have been developed over a period of several years by several workers. In addition he is now actively engaged in assembling and checking the test section and in integrating the test section into the test rig and the test instrumentation.

In the original proposal (submitted on November 3, 1976) the following "Work Statement" was included:

1. To rebuild the existing heat pipe test facility using new sophisticated instrumentation currently on hand which has been purchased by the School of Mechanical Engineering and will be provided at no cost to the proposed project;
2. To design and fabricate an elaborate and well instrumented test section which can accommodate a number of capillary structures;
3. To obtain transient heat pipe operating data both below, near and above the critical point for Freon 11 using several capillary structures;
4. To continue theoretical development of a mathematical model of the transient heat pipe problem including partial and complete dryout conditions; and
5. To utilize results of the experimental program for checking and altering the theoretical formulation

Item 1 in the "Work Statement" has essentially been completed and item 2 has nearly been completed. Final checking and assembly of the test section are now being carried out and should be completed soon. Considerable progress has been made in regard to item 4. However it is expected that the theoretical approach will be under development throughout the remainder of the grant period. Work should begin on item 3 within about one month and continue into the spring of 1979. Item 5 will be, of course, the final task in the current year's work. It is

expected that reliable experimental data will be available for use in checking the theoretical work beginning in the winter of 1979.

PERSONNEL

Dr. Gene Colwell has acted as principal investigator during the first year of the grant. His contributions to the project have consisted of general technical and money management, personnel direction, design and selection of elements for the test rig and the test section, and direction of the theoretical effort. A Ph.D. candidate has been supported one third time during the initial year of the grant. His efforts have been largely aimed at improving the theoretical approach which has been developed over a period of approximately five years and performing a continuing search and digestion of literature relative to the grant work. An M.S. candidate has also worked on the project (at no cost to NSF). He has made significant contributions to the effort in the area of programming and numerical analysis. He graduated in the spring of 1978 and wrote a "Special Problem" report on his heat pipe work for which he received twelve quarter hour of graduate credit. Several electrical and mechanical technicians have been involved in building test equipment and a portion of their salary has been paid by the grant.

FINAL REPORT

Period Covering July 15, 1977 to December 31, 1979

**HEAT PIPE STARTUP FROM
THE SUPERCRITICAL STATE**

**Prepared for
THE NATIONAL SCIENCE FOUNDATION
Heat Transfer Program
Grant ENG—7704130**

March 15, 1980

**GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF MECHANICAL ENGINEERING
ATLANTA, GEORGIA 30332**

1980



GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION
SPONSORED PROJECT INITIATION

ALB

Date: August 15, 1977

Project Title: Heat Pipe Startup from the Supercritical State

Project No: E-25-678

Project Director: Dr. Gene T. Colwell

Sponsor: National Science Foundation

Agreement Period: From 7/15/77 Until 12/31/78
(12-month budget period plus flexibility period)

Type Agreement: Grant No. ENG77-04130, dated 8/5/77

Amount: \$29,400 NSF
2,660 GIT (E-25-341)
\$32,060

Reports Required: Annual Technical Letter Report; Final Technical Report; Summary of Completed Project

Sponsor Contact Person (s):

Technical Matters

Dr. Win Aung, Director
Heat Transfer Program
Engineering Chemistry and
Energetics Section
Division of Engineering
National Science Foundation
Washington, D. C. 20550

Contractual Matters
(thru OCA)

Ms. Mary Frances O'Connell
Grants Specialist, Area 4
Division of Grants and Contracts
National Science Foundation
Washington, D. C. 20550
(202) 632-2858

Defense Priority Rating: N/A

Assigned to: Mechanical Engineering (School/Laboratory)

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Library, Technical Reports Section
Office of Computing Services
Director, Physical Plant
EES Information Office
Project File (OCA)
Project Code (GTRI)
Other _____

HEAT PIPE STARTUP FROM THE SUPERCRITICAL STATE

FINAL REPORT

To

The National Science Foundation
Heat Transfer Program

Grant ENG-7704130

July 15, 1977 to December 31, 1979

By

The School of Mechanical Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332

March 15, 1980

FINAL REPORT
National Science Foundation
Heat Transfer Program

Grant ENG-7704130

ENDORSEMENTS:

G. T. Colwell
Principal Investigator

S. Peter Kezios, Director
School of Mechanical Engineering

W. M. Sangster
Dean of Engineering

NATIONAL SCIENCE FOUNDATION Washington, D.C. 20550		FINAL PROJECT REPORT NSF FORM 98A			
PLEASE READ INSTRUCTIONS ON REVERSE BEFORE COMPLETING					
PART I-PROJECT IDENTIFICATION INFORMATION					
1. Institution and Address School of Mechanical Engrg. Georgia Institute of Tech. Atlanta, Georgia 30332	2. NSF Program Heat Transfer	3. NSF Award Number ENG-7704130			
	4. Award Period From 7-15-77 to 12-31-79	5. Cumulative Award Amount \$59,100			
6. Project Title Heat Pipe Startup from the Super Critical State					
PART II-SUMMARY OF COMPLETED PROJECT (FOR PUBLIC USE)					
(See attached sheet)					
PART III-TECHNICAL INFORMATION (FOR PROGRAM MANAGEMENT USES)					
1. ITEM (Check appropriate blocks)	NONE	ATTACHED	PREVIOUSLY FURNISHED	TO BE FURNISHED SEPARATELY TO PROGRAM	
				Check (✓)	Approx. Date
a. Abstracts of Theses		X			
b. Publication Citations				X	12-31-80
c. Data on Scientific Collaborators		X			
d. Information on Inventions	X				
e. Technical Description of Project and Results		X			
f. Other (specify) Significant Research Accomplishments		X			
2. Principal Investigator/Project Director Name (Typed) Dr Gene T. Colwell		3. Principal Investigator/Project Director Signature		4. Date 3-36-80	

II. Summary of Completed Project

The purpose of this project was to study experimentally and theoretically the transient operation of heat pipes at temperatures below and in the vicinity of the critical point. A test facility has been designed and constructed which can be used for obtaining experimental data in a wide variety of heat transfer studies. In addition a well instrumented heat pipe with a circumferential and central slab capillary structure has been designed and fabricated. The test heat pipe has been operated with refrigerant 11 below and in the vicinity of the critical point and detailed transient measurements have been made both internally and externally for a variety of operating conditions. Unique data has been obtained which will be published in the open scientific literature which will be of great use to researchers studying thermophysical properties in the vicinity of the critical point, to heat pipe designers, to designers of heat exchanger equipment, and to researchers in other fields where transient capillary action is important.

A theoretical study of transient heat pipe operation, which was started several year ago, has been continued during the term of this grant and the experimental data obtained has been used to improve the model and to help make the computer program based on the model more realistic and more useful.

III.e. Technical Description of Project and Results

The steady state performance of capillary structures, including heat pipes, operating well below the thermodynamic critical temperature is reasonably well understood. The transient operation of such devices is much less well understood. This is particularly true when partial or complete dryout occur, when rewetting occurs, and when fluid operating temperatures approach the critical value either from the subcritical region or the supercritical region. The goal of this project has been to study in detail the transient operation of heat pipes under normal design conditions and under conditions which cause the working fluid to approach the critical point. The study has included both theoretical and experimental approaches.

The Equipment

A test stand has been designed and constructed which can accomodate a wide variety of heat transfer experiments. It incorporates equipment for vacuum pumping, working fluid loading, heating, a coolant loop for removing thermal energy from the test section and measurement and recording of temperatures, pressures, and flow rates. The test section consists of a well instrumented stainless steel heat pipe of 80 cm length and 1.9 cm outside diameter. The internal capillary structure consists of two circumferential layers of 100 mesh stainless steel screen along the inside wall of the pipe and a central slab consisting of four layers of 40 mesh stainless

steel screen covered on both sides by two layers (four layers total) of 100 mesh stainless steel screen. The test section is supplied heat from an electric clamshell heater with heating elements cast inside a ceramic material and cooled by circulating a silicone fluid through an annulus around the cool end of the heat pipe. The heated section is 15.2 cm in length and the cooled section is 12.5 cm in length. The silicone fluid passes through a constant temperature bath which has an electric heater and a water cooling coil for controlling the bath exit temperature.

Seventeen very small stainless steel sheathed thermocouples are imbedded in the central slab of the capillary structure inside the heat pipe. In addition three thermocouples are placed in the vapor region in the interior of the heat pipe. One each is placed in the heated, adiabatic, and cooled sections. Eighteen thermocouples are placed along the outside of the heat pipe and in the cooling jacket and one is placed at inlet and one placed at exit to the cooling jacket. A high temperature high pressure pressure transducer is connected to the vapor region in the adiabatic section. Refrigerant 11 has been used as a working fluid throughout the experimental work since its critical temperature of 198°C and critical pressure of 43.2 atmospheres are relatively easy to work with.

Experimental Results

The test section has been operated under a wide variety of situations so as to determine characteristics near design conditions and far from design conditions. When

operating at modest heat transfer rates with coolant inlet temperatures well below the critical value for Refrigerant 11 the heat pipe operated very smoothly easily accommodating abrupt changes in heating rates, coolant flows and inlet coolant temperatures. Temperatures were nearly uniform in the axial direction in the slab and only small gradients existed in the vapor region along the length of the pipe. The pressure transducer indicated values that were very close to saturation pressures corresponding to measured vapor temperature in the evaporator region. As an example in one test the entire test section was initially isothermal at 24°C. Suddenly the temperature of the silicone fluid entering the cooling jacket was raised to 37°C and heat was added at the evaporator end. All internal temperatures increased smoothly and after about one and one half hours the operation was nearly steady. At that time all slab readings were very close to 89.9°C, the vapor temperature varied from 90.6°C in the heated region to 90.2 in the cooled region, and 67.8 watts of thermal energy was being picked up in the cooling jacket.

In another test, which was conducted nearer to the critical point but with all temperatures subcritical, the test section was initially at 135°C. Inlet cooling jacket temperature was quickly taken to 62°C and heat was added. After 90 minutes of operation the slab temperature varied from 145.8°C in the heated end of the pipe to 145.0°C in the cooled end. Vapor temperature was 151.9°C in the evaporator

section, 148.8°C in the adiabatic section, and 145.5°C in the condenser section. Vapor pressure was initially 263 psia and at steady state was 314 psia while the heat transfer through the condenser section increased to a steady state value of 110.8 watts.

In still another test the heat pipe was operated in the subcritical region but even closer to the critical temperature than the previously described test. In this experiment the test section was initially at 41°C . Heating was suddenly started and silicone fluid was introduced to the cooling section at 73°C . It is clear that partial dryout of the evaporator occurred in this case and that large temperature gradients existed within the heat pipe. The vapor temperature at steady state varied from 180.5°C to 164.5°C , the temperature in the driedout section of the slab varied from 176.6°C to 167.1°C , and the wetted portion of the slab was nearly uniform at a temperature of 164.0°C . The measured pressure was 450 psia and the steady state heat transfer was 131.6 watts.

An experiment was concluded where the heated end of the test section was taken into the supercritical region. This was accomplished by heating with high intensity in the evaporator section while at the same time introducing the coolant on the condenser end at an relatively high temperature. The heat pipe was initially at room temperature. Suddenly heat was added and coolant was introduced at 100°C . After about 30 minutes partial dryout began and very large temperature gradients developed throughout the heat pipe including the

slab. For example after 85 minutes, temperatures within the slab varied from 305.0°C to 145.2°C while heat picked up in the condenser was only 47.7 watts. The heat pipe clearly was not operating in a desirable manner and a good portion of the working fluid was in the supercritical region. In a continuation of this experiment heating was suddenly stopped and coolant inlet temperature was set at 90°C. It was clear from the transient temperature distributions in the slab that a rewetting of the capillary structure was occurring. After 85 minutes about half of the axial length of the structure was rewetted and all temperatures were well below the critical temperature.

Many other subcritical and supercritical heating and cooling experiments were conducted.

Theoretical

A mathematical model of transient heat pipe operation has been under development by the principal investigator and several graduate students over a period of about five years. Development of this model and associated computer programs has continued during the term of this grant. The experimental data which has been obtained under this grant has been extremely useful in checking the validity of assumptions which were made in modelling the phenomena under study. As expected, it has been necessary to modify several equations and solution techniques. The theoretical work has progressed to a point where very accurate predictions can be made of transient heating and cooling operations in

the subcritical region. Predictions of partial dryout and cooldown from the supercritical state, while not as accurate as those in the subcritical region, are good. Computer running time is always a problem with complex programs which must utilize large numbers of grid points. However, it is believed that computational costs for this program on currently available large sized computers will be reasonable.

III. f. Significant Research Accomplishments

The transient behavior of capillary structures in the vicinity of the critical point is not well understood. This is particularly true in those cases where fluid flow and heat transfer are occurring. In fact, even at temperatures well below the critical value there has been little detailed study of the phenomena associated with transient operation of capillary structures under heavy thermal loading. There has existed a need by designers for some time for an in depth understanding of these phenomena. The present experimental and theoretical study was undertaken in an effort to gain more insight into these problems. It is felt that the information resulting from this program will be of great use to workers in the areas of heat pipes, metal casting, refrigeration, blood studies, supercritical boilers, and soil seepage.

A heat pipe with circumferential and central slab capillary structure was operated with Refrigerant 11 from near room temperature to well above the critical temperature for this fluid under a variety of transient heating and cooling conditions. The heat pipe was very well instrumented internally as well as externally so that it was possible to measure distributions of temperature within the capillary structure, in the vapor region and outside of the pipe. Pressure was also measured within the test section.

It was found that operating the heat pipe at moderate heat fluxes at temperatures well below the critical value

resulted in very stable operation under both transient and steady conditions. Abrupt changes in independent parameters at either the heated or cooled ends could be easily handled by the device. Vapor temperatures were slightly higher than those in the slab and decreased from a maximum in the evaporator section to a minimum in the condensing section. Temperatures were very nearly constant in the slab all along the approximately 80 cm length of the heat pipe. Measured vapor pressure corresponded closely to saturation pressure at the highest measured vapor temperature, i.e., in the evaporator section

As more heat was transferred through the test section and as inlet temperature to the condenser jacket was increased, of course internal pressures and temperatures increased significantly. This is normally the way that a heat pipe performs. However, it is significant that at relatively high thermal loading even under conditions where no capillary dryout occurred and all temperatures were subcritical, rather large temperature gradients existed in the vapor region and vapor temperatures were considerably larger than liquid temperatures which were still very uniform along the axis of the test section.

As the thermal loading and (or) inlet coolant temperatures are increased, a portion of the evaporator section of the capillary structure will dry out. It is possible to operate the heat pipe under steady conditions with no liquid in some

part of the capillary structure and if thermal load is reduced rewetting will occur. Under steady operation with partial dryout it is found that very large temperature gradients exist in the vapor phase, there is a large temperature difference between vapor and liquid and that temperatures in the dried out part of the slab are much larger than in the wetted portion.

When thermal duty of the pipe and inlet coolant temperature are increased so that internal temperatures approach the critical, temperatures in the dried out capillary and vapor regions approach values far above the critical temperature. Heat transport capability decreases significantly and very large temperature gradients occur throughout the interior of the heat pipe as well as along the outside of the test section.

Experiments were conducted to determine the rewetting and startup characteristics of the test section. It was found that when the heat pipe was initially supercritical and was suddenly cooled at the condenser end with no heat added at the evaporator it would rewet and then after a rather long time it could be operated normally.

A mathematical model of the transient operation has been developed and it has been found to predict rather well the characteristics which were observed experimentally.

The data gathered under this grant is unique in many respects and it is felt that the theoretical work may also be of use to many researchers. The work will be reported in the open scientific literature.

III. Personnel Supported

Dr. Gene T. Colwell has been supported 25% time during two academic years and 66% time during two summer terms. He has been responsible for overall direction of the project and in addition he has participated directly in design, fabrication and operation of the test equipment. He has also directed and participated in the theoretical portion of the work.

Won Son Chang has been supported 1/3 time for two calendar years. His primary responsibility has been in gathering and reducing experimental data and in improving the theoretical model. It is expected that he will receive a Ph.D. degree in June of 1980.. His thesis is devoted to this project.

Technicians have been supported under the grant to build the test rig and to assemble and test the instrumentation.

Other Graduate Students have and are currently working on the project. At this time three Ph.D. candidates who are supported with other funds are working in the heat pipe laboratory and will make use of the equipment built under this grant.

III. Theses

(See Attached Sheets)

REQUEST FOR APPROVAL OF THESIS TOPIC

JUL 26 1979

DATE May 30, 1979

NAME	WON	SOON	CHANG
	First	Middle	Last

request approval to prepare and present in partial fulfillment of the requirements for the degree of Ph. D
a thesis entitled as follows:

HEAT PIPE STARTUP FROM THE SUPERCRITICAL STATE

APPROVED:

Signed:

C. N. Director of SchoolGraduate Student request approval of thesis topic.Thesis Advisor5-30-79

30221

Box No.

Member Reading Committee or Thesis Advisory Committee7-7-79M. E.Dean, Graduate Division7/26/79Member Reading Committee or Thesis Advisory Committee7-20-79J. D. HestleyMember Reading Committee or Thesis Advisory Committee7/24/79Member Reading Committee or Thesis Advisory Committee7-20-79M. E.

*Prepare original only - Graduate Division will release copies.

A program is proposed which could contribute toward a better understanding of the transient behavior of heat pipes. The objects of the proposed thesis are; to build and design a well instrumented heat pipe test facility and test section; to obtain transient heat pipe operating data below, near and above the critical point for Freon 11; to use this data to check and suggest modifications of an existing theoretical model; and to continue theoretical development of a mathematical model of the transient heat pipe problem.

It is anticipated that the data obtained in this study will be of great use in many other fields where capillary action is important. These fields include casting of various materials, refrigeration, soil seepage, electrically superconducting equipment, absorption processes, blood flows, and botanical and biological processes.

GEORGIA INSTITUTE OF TECHNOLOGY
School of Mechanical Engineering

SPECIAL PROBLEM

INSTRUCTOR: G. T. Colwell

LEVEL: Graduate

TITLE: Design of a Freon 11 Heat Pipe

PROBLEM STATEMENT: The student will alter and update an existing computer program which was developed at Georgia Tech for the purpose of designing heat pipes. He will then use the revised program to predict the transient behavior of a Freon 11 heat pipe operating below and above the critical point. The results of this theoretical work will then be used as a guide in designing a test rig which will be used to obtain experimental data or transient capillary action in the vicinity of the critical point.

FINAL REQUIREMENTS: Progress reports will be submitted at the end of the first two quarters and a final report will be issued at the end of the third quarter.

CREDIT: 0-9-3

PREREQUISITES: Graduate Standing /

APPROVAL:

for Stothe P. Kezios, Director
School of Mechanical Engineering

6-15-77
Date

STUDENT ACCEPTED:

Signature of Student

8/1/77
Date

FINAL REPORT AND
GRADE:

A (Accepted)
(Instructor)

3-10-78
Date

(Director)

9-6-77
Date