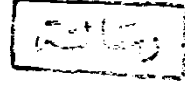


AIN SHAMS UNIVERSITY
FACULTY OF ENGINEERING



ENTRAINMENT AND WICKING LIMITS FOR HEAT PIPES

By

Ramadan Mohamed Abd El-Aziz Amer



A Thesis

Submitted for the Degree of

Doctor of philosophy

in Mechanical Power Engineering



621.8672
R-M

u9512

Supervised By

Prof. Clayton T. Crowe

Prof. Adel A. El'Ehwany

Dr. Mahmoud M. M. Abo El-Nasr

Cairo - 1993



بسم الله الرحمن الرحيم

رب إشرح لي صدري و يسر لي أمري و أحلل عقدة من لساني
يفقهوا قولي

صدق الله العظيم

In the name of Allah, Most Gracious, Most Merciful

**"O my Lord! Expand me my breast; Ease my task
for me; And remove the impediment From my
speech. So they may understand What I say"**

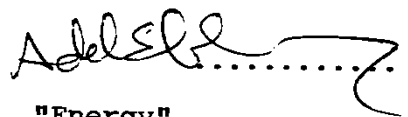
AL-QURAN, TAHA 25-28



SUPERVISORS

Prof. CLYTON T. CROWE	Mecanical and material Engineering Dept. Washington State University, U.S.A.
Prof. A. EL'EHWANY	Chairman of the Mechanical Engineering Dept. "Energy" Faculty of Engineering, Ain Shams University, Cairo, Egypt.
Associ. Prof. M. ABO EL-NASR	Mechanical Engineering Dept. "Energy" Faculty of Engineering, Ain Shams University, Cairo, Egypt.

Examiners Committee

<u>Name, Title & Affiliation</u>	<u>Signature</u>
1- Prof. M. M. Helal Mechanical Power Engineering Dept. Faculty of Engineering, Cairo University.	
2- Prof. S. M. Abd El-Ghany Mechanical Engineering Dept. "Energy" Faculty of Engineering, Ain Shams University.	
3- Prof. A. A. El'Ehwany Chairman of Mech. Engineering Dept. "Energy" Faculty of Engineering, Ain Shams University.	
4- Assoc. Prof. M. M. Abo El-Nasr Mechanical Engineering Dept. "Energy" Faculty of Engineering, Ain Shams University.	

STATEMENT

This dissertation is submitted to Ain Shams University for the degree of Doctor of Philosophy in Mechanical Power Engineering.

The work included in this thesis was carried out by the author in the Department of Energy and automotive Engineering, Ain Shams University and Department of Mechanical and Material engineering Washington State University, from April 13, 1987 to Jan. /2 ,1993.

No part of this thesis has been submitted for a degree or a qualification at any other University or Institution.

Date : January 12th 1993

Signature : Ramadan

Name : Ramadan M. Abd El-Aziz Amer

ACKNOWLEDGEMENTS

The author wishes to express his sincere thanks to GOD, for his helps and gifts, that have enabled him to achieve this thesis.

Deep gratitude and sincere thanks are to Prof. C.T. Crowe, for his advice, guidance and valuable suggestions during the various stages of this work.

Sincere thanks and deep gratitude are also due to Prof. A.A. El-Ehwany, for his encouragement and help in supervising this research work.

The author is also grateful to Dr. M.M. Abo El-Nasr, for his helpful suggestions and for his cooperation during the course of this work.

Thanks are also due to the Manager and to the Staff of the workshops of the Mechanical and Material Engineering Department, Washington State University, who have helped through the suggestions, designing and installation of the

experimental apparatus of this work.

Sincere thanks also go to the members of the Faculty of Engineering, Zagazig University who have helped him to this scientific channel and who facilitate completing his file.

Appreciations are also due to the members of the Faculty of Engineering, Ain Shams University who have accepted the author registration and helped him in the design of the experimental apparatus, in the design and fabrication of the porous measuring test rig and in the preparation of the theoretical part of this study.

Thanks are also due to the Egyptian government, who provided the financial support for me and for the research work along two years.

Appreciation and deep gratitude is also due to my mother, brothers, sister, wife and family , without whose support and encouragement, this work would not have been possible.

SUMMARY

A heat pipe is a device capable of high heat transfer rates under isothermal conditions. It consists of a container, such as a pipe, whose interior wall is lined with wick structure saturated with the working fluid. Heat transfer in the evaporator region of the heat pipe causes the liquid in the wick to evaporate and flow into the condenser zone where it is condensed. The return of liquid from the condenser to the evaporator occurs due to the capillary forces in the wick that create a surface tension pressure differential to overcome the vapor and liquid pressure drops, including that due to gravitation or other externally imposed body forces. For a given pipe geometry and working fluid, the thermodynamic and flow characteristics determine the transport limits; namely, viscous, sonic flow of vapor, entrainment, capillary, and boiling. In the present study, both the entrainment limit and the wicking (capillary) limit are investigated.

Experiments were carried-out on copper heat pipes with copper porous wick using either water or R-11 as the working fluids. The pipes were tested at different orientations and the maximum performance was measured. Five heat pipes were

operated at the same time and angle of inclination, and had similar diameter, evaporator length, adiabatic length, condenser length, working fluid, operating pressure and temperature, and heat flux. However they had different porous wick thicknesses. The heat pipe was made of copper, 450 mm in length, 15 mm in diameter, and lined internally by a copper porous wick of 2 mm, 2.8 mm, 3.6 mm, 4.4 mm, and 5.2 mm thicknesses.

The experimental results are shown to be in a quiet agreement with the theoretical predictions at some specific situations, but generally disagree. New correlations for both the wicking limit and the entrainment limit are presented in which the thickness and properties of the wick are playing a major role.

CONTENTS

<u>Description</u>	<u>Page</u>
ACKNOWLEDGEMENTS	i
SUMMARY	iii
LIST OF SYMBOLS	viii
CHAPTER 1 INTRODUCTION	1
Limitation and Characteristics of the Heat Pipe	7
1.1 Viscous Limit	7
1.2 Sonic Limit	9
1.3 Entrainment Limit	10
1.4 Wicking Limit	10
1.5 Boiling Limit	11
CHAPTER 2 LITERATURE SURVEY	14
2.1 Introduction	14
2.2 Heat Pipe Performance	15
2.3 Heat Pipe Material	28
2.4 Heat Pipe Working Fluid	36
2.5 Heat Pipe Application	38
CHAPTER 3 OBJECTIVE AND DESIGN CONSTRAINTS	43
3.1 The Working Fluid and the Temperature Range	44
3.2 Container and Wick Material	46
3.3 Heat Pipe Parameters	52

CHAPTER 4	EXPERIMENTAL INVESTIGATION	55
4.1	Test Set-up	55
4.2	Heat Pipe Design and Instrumentation	61
4.2.1	Working Fluid	61
4.2.2	Capillary Structure and Container	62
4.2.3	Instrumentation	66
4.3	Fabrication Process	71
4.3.1	Capillary Structure	71
4.3.2	End Caps of the Heat Pipe	73
4.3.3	Evaporator and Condenser	73
4.3.4	Cleaning of the Test Tubes and End Caps	76
4.3.5	Heat Pipe Assembly, Evacuation and Charging	78
4.3.6	Testing Procedure	79
4.3.7	Procedure of Experiments and Performance Prediction	81
CHAPTER 5	REPRESENTATION OF THE EXPERIMENTAL RESULTS	83
5.1	Introduction	83
5.2	The Effect of the Orientation Angle	84
5.3	The Working Fluid Properties	101
5.4	Effect of the Wick Thickness	140
5.5	Effect of the Adiabatic Section Length	142
5.6	Effect of the Wick Characteristics	145
5.7	Heat Transfer Behavior	148

CHAPTER 6	DISCUSSION OF THE EXPERIMENTAL RESULTS AND CORRELATIONS	154
6.1	The Wicking Limit	156
6.2	The Entrainment Limit	157
CHAPTER 7	CONCLUSION AND RECOMMENDATIONS FOR THE FUTURE WORK	167
7.1	Conclusion	167
7.1.1	Wicking Limit	167
7.1.2	Entrainment Limit	169
7.1.3	Orientation, Fluid Properties and Wick Specifications	170
7.2	Recommendations for the Future Work	171
REFERENCES		173
APPENDICES		183
Appendix A		184
Appendix B		191
Appendix C		192
Appendix D		193
Appendix E		195
Appendix F		196
Appendix G		197
Appendix H		199
Appendix I		201

LIST OF SYMBOLS

A	Cross-Sectional Area	m^2
D	Diameter	m
d	Pore Diameter	m
D_m	Mean Grain Diameter	m
g	Local Gravity Acceleration	m/s^2
h	Film Heat Transfer Coefficient	W/m^2K
k	Fluid Permeability of wick	m^2
L	Latent Heat of Vaporization	J/kg
l	Length	m
M	Liquid Transport Factor (Heat Flux)	W/m^2
m	Liquid Fill	kg
$\dot{m}$	Mass Flow Rate	kg/s
P	Pressure	Pa
P_c	Capillary Pressure	Pa
Q	Rate of Heat Flow	W
R	Radius	m
R_c	Thermal Resistance	$m^2 K/W$
Re	Reynold's Number	—
R_g	Gas Constant	J/kgK
r_c	Capillary Radius	m
S	Surface Area	m^2
T	Temperature	K
t	Temperature	$^{\circ}C$
V	Velocity	m/s
U	Overall Heat Transfer Coefficient	W/m^2K
U.T.S.	Ultimate Tensile Stres	N/m^2
X	Axial Distance	m

Subscripts

a	Adiabatic
Al	Aluminum
c	Condenser
E	Equivalent
e	Evaporator
eff	Effective
i	In
l	Liquid
m	Mean
o	Out
p	Pipe
t	Total
w	Wick
v	Vapor

Greek Symbols

α	Heat Exchange Intensity	W
Δ	Difference	—
δ	Wick thickness	m
δ_f	Film Thickness	m
ϵ	Porosity	—
θ	Contact Angle	Deg./Rad
λ	Thermal Conductivity	W/mK
μ	Dynamic Viscosity	Ns/m ²
ρ	Density	kg/m ³
σ	Liquid Surface Tension	N/m
ϕ	Angle to Horizontal	Deg.