A COMPUTATIONAL MODEL FOR
TWO-PHASE EJECTOR FLOW

by

Peter Menegay

Dissertation submitted to the Faculty of the
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of
DOCTOR OF PHILOSOPHY
in
Mechanical Engineering

APPROVED:

Alan A. Kornhauser, Chairman
Douglas J. Nelson
Demetri P. Telionis
William C. Thomas
Brian Vick

January 29, 1997
Blacksburg, Virginia

Key Words: CFD, Non-equilibrium, Refrigeration, Two-fluid, Jet
A COMPUTATIONAL MODEL FOR
TWO-PHASE EJECTOR FLOW

by

Peter Menegay
Committee Chairman: Dr. A. A. Kornhauser
Mechanical Engineering

(ABSTRACT)

A CFD model to simulate two-phase flow in refrigerant ejectors is described. This work is part of an effort to develop the ejector expansion refrigeration cycle, a device which increases performance of a standard vapor compression cycle by replacing the throttling valve with a work-producing ejector. Experimental results have confirmed the performance benefit of the ejector cycle, but significant improvement can be obtained by optimally designing the ejector. The poorly understood two-phase, non-equilibrium flow occurring in the ejector complicates this task.

The CFD code is based on a parabolic two-fluid model. The applicable two-phase flow conservation equations are presented. Also described are the interfacial interaction terms, important in modelling non-equilibrium effects. Other features of the code, such as a mixing length turbulence model and wall function approximation, are discussed. Discretization of the equations by the control volume method and organization of the computer program is described.

Code results are shown and compared to experimental data. It is shown that experimental pressure rise through the mixing section matches well against code results. Variable
parameters in the code, such as droplet diameter and turbulence constants, are shown to have a large influence on the results. Results are shown in which an unexpected problem, separation in the mixing section, occurs. Also described is the distribution of liquid across the mixing section, which matches qualitative experimental observations. From these results, conclusions regarding ejector design and two-phase CFD modelling are drawn.
ACKNOWLEDGEMENTS

I would first like to thank the individual who made this project possible and my advisor throughout my entire time as a graduate student, Dr. Alan A. Kornhauser. His patient guidance and insight into a poorly understood topic proved to be invaluable. He has contributed more to my engineering education than any other single individual, and in the process taught me what independent research is all about.

I would also like to thank my advisory committee, Drs. Nelson, Telionis, Thomas, and Vick. My meetings with them were always educational and they often provided me with a much needed reality check for what I was attempting to do. Dr. Nelson and Dr. Vick are also thanked for teaching background courses without which I could not have undertaken the project described here.

Special thanks also go to Drs. Ganeshan, Joan Moore, and Nelson for taking time out to advise me individually during the course of my work. There were many occasions when I was having trouble seeing the next step and they gave me the push I needed to continue on my own.

Thanks go to Calmac, Inc., our industrial partner and sponsor of this research. Their financial assistance and technical expertise proved indispensable in getting the EERC project launched. The Department of Commerce - Advanced Technology Program is thanked for providing the bulk of the financial assistance for the EERC project in its later years.

Finally, thanks go to my colleagues and friends who have worked with me on this project. Greg Harrell, Mike Alexandrian, Tommy Bunch, Kristoffer Ogebjer, and Hakan Snis
provided me with useful data and insight into two-phase ejector modelling. They also proved to be great lab companions during our work breaks.
# TABLE OF CONTENTS

**Chapter 1 - Introduction** .......................................................................................................................... 1

1.1 Background .............................................................................................................................................. 1

1.1.1 The Ejector Expansion Refrigeration Cycle (EERC) ......................................................................... 1

1.1.2 Ejector Design and Flow Characteristics .......................................................................................... 2

1.1.3 Project Objective: The Two-Fluid Model ......................................................................................... 6

1.2 Previous Work .......................................................................................................................................... 8

1.2.1 Work on EERC ................................................................................................................................. 8

1.2.2 Two-Phase Flow Modelling ............................................................................................................. 10

1.2.3 Currently Available Computer Programs ...................................................................................... 12

**Chapter 2 - Conservation Equations** ...................................................................................................... 15

2.1 Introduction ............................................................................................................................................ 15

2.1.1 Two-Phase Flow Formulation Methods .......................................................................................... 15

2.2 Two-Phase Conservation Equations .................................................................................................... 17

2.2.1 Conservation of Mass ...................................................................................................................... 17

2.2.2 Conservation of Momentum ............................................................................................................ 18

2.2.3 Conservation of Energy .................................................................................................................. 23

2.3 Nondimensionalization ......................................................................................................................... 24

2.4 Boundary Conditions ............................................................................................................................ 26

**Chapter 3 - Two-Phase Physical Modelling** ............................................................................................ 27

3.1 Interfacial Source Terms ......................................................................................................................... 27

3.1.1 Momentum Transfer ....................................................................................................................... 28

3.1.2 Energy and Mass Transfer .............................................................................................................. 29

3.2 Flow Regime Determination .................................................................................................................. 33

3.3 Droplet/Bubble Size ............................................................................................................................... 34

3.4 Turbulence Model .................................................................................................................................. 35

3.4.1 Wall Function Approximation ........................................................................................................ 39
3.5 Refrigerant Thermo-Physical Properties.............................................................. 43

Chapter 4 - Solution Procedure............................................................................ 44
4.1 Coordinate Transformation................................................................................. 44
4.2 Control-Volume Discretization Method.............................................................. 47
4.3 Tridiagonal Form of Equations........................................................................... 55
4.4 IPSA Based Algorithm...................................................................................... 55
4.5 Solution of Ejector Flow Problem.................................................................... 57

Chapter 5 - Results and Discussion.................................................................... 59
5.1 Introduction....................................................................................................... 59
5.1.1 Flow Regime Transition Shock.................................................................... 60
5.1.2 Recirculation................................................................................................ 61
5.1.3 Limitations of the Code.............................................................................. 66
5.2 Results for Non-Separating Conditions............................................................. 67
5.2.1 Determination of Mixing Section Inlet Conditions...................................... 67
5.2.2 Results for Mixing Section Pressure Rise.................................................. 69
5.2.3 Results Concerning Liquid Droplet Distribution.......................................... 77
5.3 Numerical Accuracy Considerations................................................................ 85

Chapter 6 - Conclusions and Recommendations.................................................. 89
6.1 Conclusions....................................................................................................... 89
6.2 Recommendations............................................................................................ 92

Appendix A - Computer Program Listing............................................................. 94
Appendix B - Derivation of Basic Equations......................................................... 134
References............................................................................................................ 143
Vita...................................................................................................................... 148
### LIST OF FIGURES

1.1 Schematic of EERC........................................................................................................... 3
1.2 Close-Up View of Ejector.................................................................................................. 4
2.1 Illustration of Interfacial Pressure Force due to Void Fraction Variation................. 21
3.1 Energy Balance on Droplet............................................................................................. 31
3.2 Turbulent Boundary Layer Regions in Mixing Section.............................................. 37
3.3 Wall Function vs. Fine Grid and Experimental Data (Razinsky, et al. [45])............. 42
4.1 Grid in Physical and Transformed Coordinates.............................................................. 45
4.2 Organization of Grid and Typical Discretization Control Volume.............................. 48
4.3 Sample Grid for Unknowns vs. Equations................................................................. 56
5.1 Code vs. Experiment with Separation (Original Ejector)......................................... 62
5.2 Experimental Mixing Sections..................................................................................... 65
5.3 Comparisons of Experimental Pressure Rise and Code Results.............................. 70
5.4 Effect of Droplet Diameter on Pressure Rise............................................................... 71
5.5 Effect of Jet/Outerwall Turbulence Constant on Pressure Rise................................. 72
5.6 Velocity and Void Fraction Profiles at Various Axial Locations............................... 73
5.7 Vapor Velocity Profile................................................................................................. 74
5.8 Liquid Velocity Profile................................................................................................. 75
5.9 Void Fraction Profile..................................................................................................... 76
5.10 Velocity Profile for Constant Droplet Diameter.......................................................... 78
5.11 Velocity Profile for Const. Droplet Dia. up to Region of Negligible Liquid.......... 80
5.12 Liquid Mass Distribution Across Domain with Closeup View................................. 82
5.13 Variation of Radial Velocity....................................................................................... 84
5.14 Error Variation with Grid Refinement........................................................................ 88
B.1 Control Volume for Derivation of Basic Equations....................................................... 135
LIST OF TABLES

5.1 Flow Conditions for Non-Recirculating Ejector................................................. 68
5.2 Program Error Criteria with Global Momentum/Continuity................................. 87
NOMENCLATURE

\( x \) axial distance
\( r \) radial distance
\( \bar{x} \) body fitted coord. system axial distance
\( \bar{r} \) body fitted coord. system radial distance
\( r_t \) top boundary of domain
\( r_b \) bottom boundary of domain
\( r'_t \) slope of top boundary
\( r'_b \) slope of bottom boundary
\( u \) axial velocity
\( uu \) upstream axial vel.
\( v \) radial velocity
\( vu \) upstream radial velocity
\( P \) pressure
\( T \) temperature
\( \alpha \) void fraction
\( h \) enthalpy or convection coefficient
\( h_{fs} \) latent heat
\( d \) droplet/bubble diameter
\( \rho \) density
\( \mu \) viscosity
\( \sigma \) surface tension
\( k \) conduction coefficient
\( c_p \) specific heat
\( \beta \) coefficient of thermal expansion
\( \tau_w \) wall shear stress
\( l_m \) mixing length
κ  turbulence constant
κ₀  turbulence constant
A  turbulence constant
C₀  turbulence constant
Cd  drag coefficient
We_{crit}  critical Weber number to find size of droplets/bubbles
D  pipe diameter
F  interfacial drag force
M  interfacial momentum transfer due to mass transfer
Γ  interfacial mass transfer (evaporation/condensation)
E_{ht}  interfacial heat transfer
E_{mt}  interfacial thermal energy transferred due to mass transfer
E_{ke}  interfacial kinetic energy transferred due to mass transfer
E_{wt}  interfacial work transfer
Re  Reynold's number resulting from non-dimensionalization
Pr  Prandtl number resulting from non-dimensionalization
Ec  Eckert number resulting from non-dimensionalization

RINTE
RINTW
RINT2N
RINT2S
RINT4N
RINT4S
RINT3M  Area/volume terms in body fitted coordinate system
subscripts/superscripts

c, cont continuous phase
d, disc discontinuous phase
int interfacial
1 liquid
v vapor
m mixture
r relative
s saturated
t turbulent
1 first phase
2 second phase
e east face of control volume
w west face
n north face
s south face