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ANALYSIS AND MODELING OF A TWO-PHASE JET PUMP OF A FLOW BOILING TEST FACILITY FOR AEROSPACE APPLICATIONS

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NOMENCLATURE

Latin Symbols

A	cross-sectional area
A_b	cross-sectional area of plenum containing secondary fluid
C_p	specific heat at constant pressure
C_v	specific heat at constant volume
D	diameter
F	friction force
f	friction factor
g	acceleration of gravity
L	length
$\dot{m}$	mass flow rate
p	static pressure
R_g	gas constant
r_a	primary nozzle exit-to-mixing throat exit area ratio, A_{ne}/A_{mi}
r_b	secondary fluid plenum exit-to -mixing throat exit area ratio, A_b/A_{mi}
r_e	entrainment ratio, $\dot{m}_s / \dot{m}_n$
r_p	jet pump compression ratio, $(p_{de}-p_s)/(p_{ne}-p_{de})$
T	absolute temperature
V	velocity

Greek Symbols

β	liquid phase-to-mixture mass ratio
γ_g	gas phase ratio of specific heats
ε	heat transfer parameter, $(T_L-T_o)/(T_g-T_o)$
η	jet pump efficiency, $r_e r_p$
ρ	density
$\bar{\rho}$	distributed phase density over total mixture volume
σ	slip parameter, V_L/V_g

Subscripts

d	zone of diffuser from downstream of shock to diffuser exit
e	exit
g	gas phase
i	inlet
L	liquid phase
m	mixing tube, mixture
n	primary nozzle
o	stagnation conditions
s	secondary fluid conditions at mixing throat entrance
sd	conditions downstream of re-equilibrium region of shock
su	conditions immediately upstream of shock
u	zone of diffuser from its inlet to upstream of shock

INTRODUCTION

Jet pumps are devices capable of pumping fluids to a higher pressure employing a nozzle/diffuser/mixing chamber combination. A primary fluid is usually allowed to pass through a converging-diverging nozzle where it can accelerate to supersonic speeds at the nozzle exit. The relatively high kinetic energy that the primary fluid possesses at the nozzle exit is accompanied by a low pressure region in order to satisfy Bernoulli's equation. The low pressure region downstream of the nozzle exit permits a secondary fluid to be entrained into and mixed with the primary fluid in a mixing chamber located downstream of the nozzle. Several combinations may exist in terms of the nature of the primary and secondary fluids in so far as whether they are single or two-phase fluids. Depending on this, the jet pump may be classified as gas/gas, gas/liquid, liquid/liquid, two-phase/liquid, or similar combinations.

The mixing chamber serves to create a homogeneous single-phase or two-phase mixture which enters a diffuser where the high kinetic energy of the fluid is converted into pressure energy. If the fluid mixture entering the diffuser is in the supersonic flow regime, a normal shock wave usually develops inside the diffuser. If the fluid mixture is one that can easily change phase, a condensation shock would normally develop. Because of the overall rise in pressure in the diffuser as well as the additional rise in pressure across the shock layer, condensation becomes more likely. Associated with the pressure rise across the shock is a velocity reduction from the supersonic to the subsonic range. If the two-phase flow entering the diffuser is predominantly gaseous with liquid droplets suspended in it, it will transform into a predominantly liquid flow containing gaseous bubbles (bubbly flow) somewhere in the diffuser.

Literature dealing with jet pumps is abundant and covers a very wide array of application areas. Example application areas includes vacuum pumps which are used in the food industry, power station work, and the chemical industry; ejector systems which have applications in the aircraft industry as cabin ventilators and for purposes of jet thrust augmentation; jet pumps which are used in the oil industry for oil well pumping; and steam-jet ejector refrigeration, to name a few. Examples of work relevant to this investigation includes those of Holmes et al. (1987), Cunningham and Dopkin (1974), Cunningham (1995), Elger et al. (1991), Marini et al. (1992), Jiao et al. (1990), Neve (1991), Bredikhin et al. (1990), and Fairuzov and Bredikhin (1995).

While past researchers have been able to model the two-phase flow jet pump using the one-dimensional assumption with no shock waves and no phase change, there is no research known to the authors apart from that of Anand (1992) which accounted for condensation shocks. One of the objectives of this research effort is to develop a comprehensive model in which the effects of phase slip and inter-phase heat transfer as well as the wall friction and shock waves are accounted for. While this modeling effort is predominantly analytical in nature and is primarily intended to provide a parametric understanding of the jet pump performance under different operating scenarios, another parallel effort employing a commercial CFD code is also implemented. The latter effort is primarily intended to model an axisymmetric counterpart of the problem in question. The viability of using the CFD code to model a two-phase flow jet pump will be assessed by attempting to recreate some of the existing performance data of similar jet pumps. The code will eventually be used to generate the jet pump performance characteristics of several scenarios involving jet pump geometries as well as flow regimes in order to be able to determine an optimum design which would be suitable for a two-phase flow boiling test facility at NASA-Marshall.

Because of the extensive nature of the analytical model developed, the following section will only provide very brief highlights of it, while leaving the details to a more complete report submitted to the NASA colleague. This report will also contain some of the simulation results obtained using the CFD code.

HIGHLIGHTS OF THE ANALYTICAL MODEL

This analysis deals with a jet pump whose primary fluid is a two-phase mixture and whose secondary fluid is either a subcooled or saturated liquid having the same chemical composition as the primary fluid. The two-phase primary fluid flows through a converging-diverging nozzle (primary nozzle) and exits at a high velocity and low pressure. The low pressure at the primary nozzle exit induces the flow of the secondary fluid which mixes with the primary fluid in a mixing section. The mixing section is typically comprised of two parts; a throat and a mixing tube. The mixing throat is a short converging section where the flow accelerates slightly and the pressure drops correspondingly. The mixing tube serves to enhance the mixing that has already started in the throat. Two common types of mixing may be employed in the mixing tube; constant pressure or constant area mixing. Literature dealing with this subject reports that the compression ratios of jet pumps employing constant-pressure mixing are a bit higher than those employing constant-area mixing. However, for the sake of simplicity, this analysis will deal with a jet pump employing constant-area mixing in the mixing tube. Nevertheless, because of the slight drop in pressure in the mixing throat, the mixing process in the latter will be handled using a more general set of fluid dynamical equations applicable to variable pressure/variable area mixing.

Because the cross-sectional area of the mixing tube is assumed constant, the pressures at the inlet and exit of the tube are assumed to take distinct values. The two-phase flow leaving the mixing tube enters a diffuser where it undergoes a normal shock across which the mixture pressure rises and the flow becomes subsonic. The flow downstream of the shock in the diffuser continues to decelerate while the pressure continues to rise until the fluid exits the diffuser.

While it is customary to expect some condensation in both the mixing tube and the diffuser primarily due to the rise in pressure, this analysis deals with a simplified case involving no phase change. Partial justification for this assumption is based on the hypothesis that the condensation of the gaseous phase due to the pressure rise may be offset by a counter effect due to the associated rise in temperature. while in a typical situation the former effect is more dominant than the latter, the hypothesis in question is assumed valid for purposes of simplifying the analysis a bit. While the model as presented does not account for phase change per se, the fact that the liquid phase-to-mixture mass ratio can be assigned separate values as we proceed from one zone to another gives the model some flexibility to artificially account for the possibility of phase change.

One of the objectives of this effort is to develop a generalized formulation for the jet pump compression ratio as well as the jet pump efficiency in terms of the relevant flow and heat transfer parameters and examine the conditions under which both quantities can be maximized. In order to achieve the above objectives, the jet pump will be divided into several sections for purposes of performing the analysis. These segments are the primary nozzle, the mixing throat, the mixing tube, the diffuser upstream of the shock, the shock layer itself and the diffuser downstream of the shock.

Primary Nozzle

The velocity, temperature, and pressure fields of both the liquid and gaseous phases for this segment of the jet pump have been resolved by Sherif et al. (1994) and the reader is advised to consult this reference as well as the longer version of this report for details.

Mixing Throat

The mixing throat is a short converging section connecting the secondary fluid plenum to the mixing tube. The plenum also contains the primary nozzle. The secondary fluid is allowed to enter the mixing tube as a liquid mist by action of the pressure drop generated by the flow of the primary stream. This mechanism of introducing the secondary fluid is one of two mechanisms typically used in jet pumps. The volume of literature dealing with the mechanism described here is massive and includes the works of Francis et al. (1972) and Tsung (1972), to name a few. The other mechanism allows the secondary fluid to be directly injected employing spray nozzles stationed at an angle to the axis of the mixing tube. Literature dealing with this mechanism of injection is not as extensive and includes the work of Fairuzov and Bredikin (1995). Details of the mathematical treatment of this section can be found in the more detailed report submitted to the NASA colleague.

Mixing Tube

The mixing tube is a constant-area duct downstream of the converging section labeled as the mixing throat. The analysis dealing with this section includes the effects of wall friction which can be expressed by:

$$F_m = \frac{\pi f_m L_m^2}{2}\left[\beta_m \sigma_m + (1-\beta_m)\right]\left[\beta_m \rho_{L,m} + \frac{(1-\beta_m) p_m}{R_g T_{g,m}}\right] V_{g,m}^2$$

To give a flavor of the nature of the analysis, the equations that follow provide a complete set for computing the mixing tube exit velocity of the gas phase as well as the mixture exit pressure:

$$V_{g,me} = \left[V_{g,mi}^2 - 2\left\{ \frac{\beta_m \varepsilon_m C_{L,m} + (1-\beta_m) C_{p,g,m}}{1-\beta_m+\beta_m \sigma_m^2} \right\} (T_{g,me} - T_{g,mi}) \right]^{\frac{1}{2}}$$

$$p_{me}=\frac{p_{mi}\Bigg[\dfrac{E_1}{2E_3}Log_e\Big\{(E_3T_{g,mi}+E_4)T_{g,mi}\Big\}+\Big\{\dfrac{2E_2E_3-E_1E_4}{2E_3E_4}\Big\}Log_e\Big\{\dfrac{E_3T_{g,mi}}{E_3T_{g,mi}+E_4}\Big\}\Bigg]}{\Bigg[\dfrac{E_1}{2E_3}Log_e\Big\{(E_3T_{g,me}+E_4)T_{g,me}\Big\}+\Big\{\dfrac{2E_2E_3-E_1E_4}{2E_3E_4}\Big\}Log_e\Big\{\dfrac{E_3T_{g,me}}{E_3T_{g,me}+E_4}\Big\}\Bigg]}$$

$$+\frac{B_2B_4}{2E_3^3E_4}\Big[2\big(E_1E_4-E_2E_3\big)\big(E_3T_{g,me}+E_4\big)Log_e\big(E_3T_{g,me}+E_4\big)-\big(E_3T_{g,mi}+E_4\big)Log_e\big(E_3T_{g,mi}+E_4\big)\big)\Big]$$

$$+2E_2E_3\Big[\big(E_3T_{g,me}+E_4\big)Log_eT_{g,me}-\big(E_3T_{g,mi}+E_4\big)Log_eT_{g,mi}\Big]$$

$$+\Big[\big(2E_2E_3-E_1E_4\big)E_3Log_eE_3-2E_1E_3E_4\Big]\big(T_{g,me}-T_{g,mi}\big)$$

$$+E_4\big(E_2E_3-E_1E_4\big)\Big[\Big\{Log_e\big(E_3T_{g,me}+E_4\big)\Big\}^2-\Big\{Log_e\big(E_3T_{g,mi}+E_4\big)\Big\}^2\Big]$$

$$-2E_2E_3E_4\Big[Log_eT_{g,me}Log_e\big(E_3T_{g,me}+E_4\big)-Log_eT_{g,mi}Log_e\big(E_3T_{g,mi}+E_4\big)\Big]$$

$$+\big(E_1E_4-2E_2E_3\big)E_4Log_eE_3Log_e\left(\frac{E_3T_{g,me}+E_4}{E_3T_{g,mi}+E_4}\right)+E_2E_3E_4\left[\Big\{Log_eT_{g,me}\Big\}^2-\Big\{Log_eT_{g,mi}\Big\}^2+Log_e\left(\frac{T_{g,mi}}{T_{g,me}}\right)^2\right]$$

$$+2E_2E_3E_4Log_eE_3Log_e\left(\frac{T_{g,me}}{T_{g,mi}}\right)+\frac{2E_2E_4^2}{T_{g,me}T_{g,mi}}\big(T_{g,me}-T_{g,mi}\big)\left[1-\frac{E_4}{4E_3}\left(\frac{T_{g,me}+T_{g,mi}}{T_{g,me}T_{g,mi}}\right)\right.$$

$$\left.+\frac{E_4^2}{9E_3^2}\left\{\frac{T_{g,me}^2+T_{g,me}T_{g,mi}+T_{g,mi}^2}{T_{g,me}^2T_{g,mi}^2}\right\}\right]\Bigg]\Bigg/\left[\frac{E_1}{2E_3}Log_e\Big\{(E_3T_{g,me}+E_4)T_{g,me}\Big\}+\left\{\frac{2E_2E_3-E_1E_4}{2E_3E_4}\right\}Log_e\left\{\frac{E_3T_{g,me}}{E_3T_{g,me}+E_4}\right\}\right]$$

$$B_2=\frac{\beta_m\varepsilon_mC_{L,m}+(1-\beta_m)C_{p,g,m}}{\sigma_m^2\beta_m+(1-\beta_m)}$$

$$B_4=\frac{4f_mL_m^2}{D_m^2}\rho_{L,m}\beta_m\big[\beta_m\rho_m+(1-\beta_m)\big]$$

$$E_1=\frac{(1-\beta_m+\beta_m\sigma_m)\big\{4f_mL_m^2(1-\beta_m)^2-D_m^2\big\}\big\{\beta_m\varepsilon_mC_{L,m}+(1-\beta_m)C_{p,g,m}\big\}}{D_m^2(1-\beta_m)(1-\beta_m+\beta_m\sigma_m^2)}$$

$$E_2=\frac{-2f_mL_m^2(1-\beta_m)(1-\beta_m+\beta_m\sigma_m)\big[(1-\beta_m+\beta_m\sigma_m^2)V_{g,mi}^2+2\big\{\beta_m\varepsilon_mC_{L,m}+(1-\beta_m)C_{p,g,m}\big\}T_{g,mi}\big]}{D_m^2(1-\beta_m+\beta_m\sigma_m^2)}$$

$$E_3=\frac{\big[R_gD_m^2(1-\beta_m+\beta_m\sigma_m^2)-4f_mL_m(1-\beta_m)(1-\beta_m+\beta_m\sigma_m)\big\{\beta_m\varepsilon_mC_{L,m}+(1-\beta_m)C_{p,g,m}\big\}\big]}{R_gD_m^2(1-\beta_m+\beta_m\sigma_m^2)}$$

$$E_4=\frac{2f_mL_m^2(1-\beta_m)(1-\beta_m+\beta_m\sigma_m)\big[(1-\beta_m+\beta_m\sigma_m^2)V_{g,mi}^2+2\big\{\beta_m\varepsilon_mC_{L,m}+(1-\beta_m)C_{p,g,m}\big\}T_{g,mi}\big]}{R_gD_m^2(1-\beta_m+\beta_m\sigma_m^2)}$$

Diffuser Portion Upstream of the Shock

Equations describing the velocity of the gas phase and the mixture pressure upstream of the shock are given below:

$$V_{g,su}=\left[V_{g,me}^{2}-\frac{2\{\beta_{m}\varepsilon_{m}C_{L,u}+(1-\beta_{m})C_{p,g,u}\}}{(1-\beta_{m}+\beta_{m}\sigma_{m}^{2})}\left(T_{g,su}-T_{g,me}\right)\right]^{\frac{1}{2}}$$

$$p_{su}=p_{me}\left(\frac{T_{g,su}}{T_{g,me}}\right)^{n_{u}}$$

Shock Wave Analysis

Details of this analysis can be found in Jackson et al. (1996).

Diffuser Portion Downstream of the Shock

Equations describing the velocity of the gas phase and the mixture pressure at the diffuser exit are given below:

$$V_{g,de}=\left[V_{g,sd}^{2}-\frac{2\{\beta_{d}\varepsilon_{d}C_{L,d}+(1-\beta_{d})C_{p,g,d}\}}{(1-\beta_{d}+\beta_{d}\sigma_{d}^{2})}\left(T_{g,de}-T_{g,sd}\right)\right]^{\frac{1}{2}}$$

$$p_{de}=p_{sd}\left(\frac{T_{g,de}}{T_{g,sd}}\right)^{n_{d}}$$

RESULTS OF CFD SIMULATION

Figures 1 and 2 provide sample results of simulating the flowf in a jet pump for both a two-dimensional as well as an axisymmetric version of this problem.

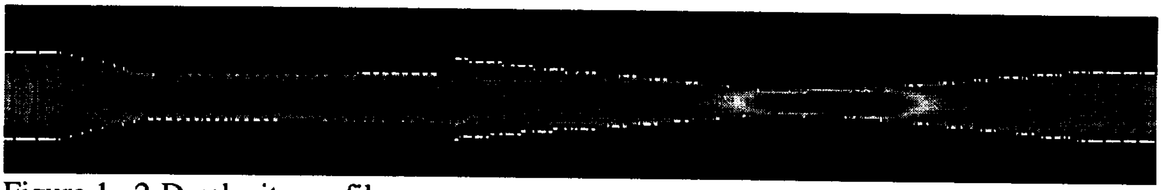

Figure 1. 2-D velocity profile.

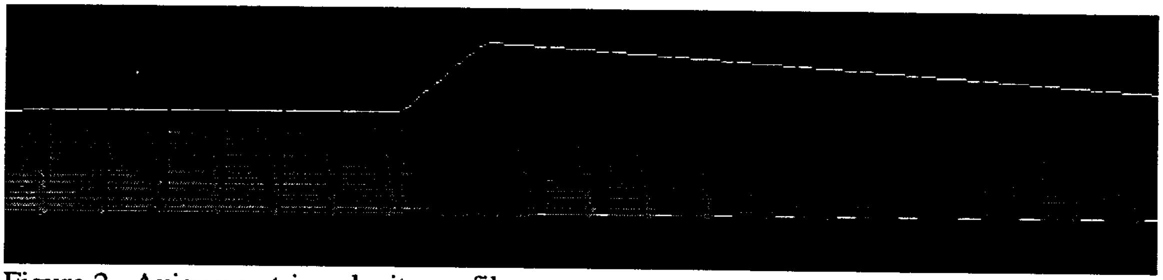

Figure 2. Axisymmetric velocity profile.