

Entrained Sprays from Meshed Interface Occurring in a Heat Pipe

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Nomenclature

L_1 = mesh length
 L_2 = mesh height
 Re_{L1} = Reynolds number based on L_1

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- V_{fg} = gas velocity relative to liquid
- We_{L1} = Weber number based on L_1
- μ = viscosity
- ρ = density
- σ = surface tension

Subscripts

- f = liquid or water
- g = gas or air

Introduction

The motivation for this work resulted from the search for innovative designs which could help prevent dry-out in two-phase heat transfer devices such as heat pipes or capillary pumped loops.¹ In these systems, dry-out may occur as a result of liquid entrainment through the screen-mesh interface by the vapor flow above it. When the vapor velocity exceeds some critical velocity, at the interface the vapor tears off a portion of the liquid forming an entrained droplet. Since the liquid entrainment reduces the rate of liquid return from the condenser to the evaporator, the overall heat transfer is significantly reduced and dry-out of the evaporator section may occur. The maximum possible heat transfer, therefore, is limited by a design vapor velocity that must be below the critical velocity. This is particularly true when the entrainment limit occurred before the onset of other limits such as a sonic, capillary, or boiling limit.

As a first approach to the problem, an aerodynamic simulator of entrainment was developed which did not incorporate the heat transfer aspects.² Using this simulator, an experimental study was performed to investigate the parameters governing the liquid (water) entrainment caused by a high-speed airstream flowing over a saturated screen-mesh interface. In an attempt to better understand the effect of the various parameters, experimental correlations for both critical velocity and droplet Sauter mean diameter (SMD) for entrained sprays were determined.

Experiment and Mesh Configurations

The test channel shown in Fig. 1 was constructed to simulate the mesh interface between a water reservoir and fully developed turbulent airflow. The liquid droplet SMDs of entrained sprays were measured using a nonintrusive laser diffraction particle analyzing technique,³ assuming a Rosin Rammler two-parameter distribution.⁴ Since the entrainment occurred in an intermittent nature and produced periodic bursts of spray, a specially designed synchronization technique⁵ utilizing the light extinction as a triggering source was employed in order to ensure statistical consistency in the measurement (Fig. 2). The light obscuration, which is a measure of the spray penetration, is detected by the center diode. The obscuration level increased as the spray penetrated the laser beam and decreased as the spray left the beam. When the obscuration level exceeded a specified level, the trigger box sent out a square pulse initiating the data taking by the ring diodes. The entrainment onset velocity was determined to be the air velocity at which the droplet size measurement was initiated as the entrained droplet concentration matched the specified triggering obscuration level (approximately 8% for the present study).

The interface between the air and water was entirely covered with a thin aluminum sheet with the exception of a small section 58-mm long near the channel exit. This section was covered with a layer of copper-wire mesh. The cross section of the air channel had rectangular dimensions of 25 by 32 mm. The gas Reynolds number based on the channel hydraulic diameter (28 mm) ranged from 5.0×10^4 to 1.2×10^5 . The lengthy entrance region of over 30 times larger than the hydraulic diameter was needed to establish fully developed airflows for the mesh-interface region.⁶ The channel side walls were fabricated from glass windows to view the inter-

face, and the water feed rate was adjusted to maintain a properly primed wick with neither flooding nor detachment of the meniscus from the mesh surface. A detailed description of the experimental test facility has been reported previously.²

Two parameters were varied during the course of the experiment. First was the air velocity, which ranged from 27 to 64 m/s and resulted in duct Reynolds numbers of approximately 5.0×10^4 to 1.2×10^5 . The second parameter represents the dimensions of the copper wire mesh. As illustrated in Fig. 3, these had a wire spacing, L_1 , ranging from 0.58 to 3.09 mm and a L_1/L_2 ratio, ranging from 2.07 to 3.47. The measurement of critical velocities and SMDs were found to be insensitive to the water feed rate which ranged from 0.5 to 2.0 ml/s.

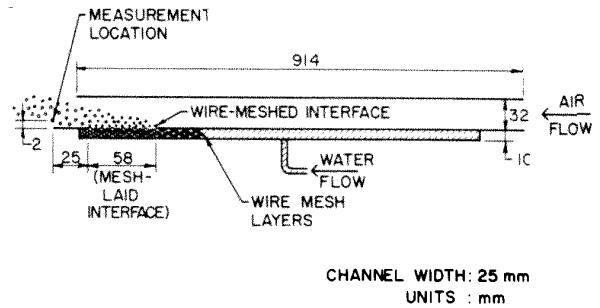


Fig. 1 Schematic representation of the test channel and flow system.

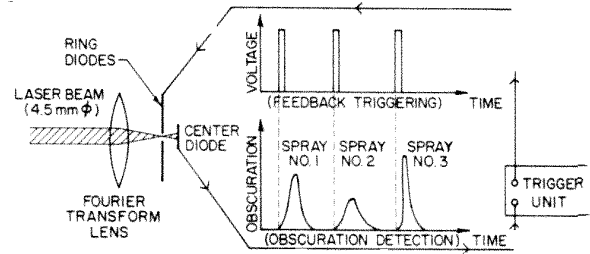
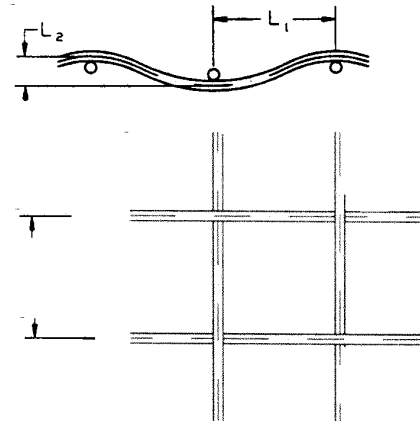


Fig. 7 Schematic illustration of the synchronization scheme for laser diffraction technique using the light obscuration as a triggering



Mesh Number	Wire Diameter	L_1 Mesh Spacing	L_2 Mesh Height	L_1 / L_2
8 × 8	0.64	3.09	0.89	3.47
16 × 16	0.22	1.35	0.43	3.10
40 × 40	0.20	0.58	0.28	2.07

Note: All lengths are in millimeters.

Fig. 3 Detailed configuration and dimensions of copper-wire meshes evaluated.

Analysis

The critical velocity for entrainment onset V_{fg} is clearly a function of the mesh dimensions and the properties of the gas and liquid:

$$V_{fg} = f(L_1, L_2, \mu_f, \mu_g, \sigma, \rho_f, \rho_g) \quad (1)$$

The hydraulic diameter of the channel is not included since the entrainment characteristics are determined by the mesh dimensions and are independent of the channel dimensions. The entrainment is a local phenomenon occurring primarily within the interface surrounded by a single mesh. In other words, the mesh geometry and scale dominate the entrainment. Different sizes of the air channel are not likely to change the entrainment characteristics as long as the mesh size and geometry remain unchanged.

Using the Buckingham-PI theorem,⁷ a correlational form between dimensionless PI parameters was obtained as

$$\frac{\rho V_{fg}^2 L_1}{\sigma} = A \left(\frac{L_1}{L_2} \right)^B \left(\frac{\mu_g}{\sqrt{\rho_g \sigma L_1}} \right)^C \left(\frac{\mu_f}{\mu_g} \right)^D \left(\frac{\rho_f}{\rho_g} \right)^E \quad (2)$$

where the left side represents We_{L1} , defined with a length scale of the mesh spacing L_1 and the second parameter on the right side is equivalent to the viscosity group as defined in Ref. 8. The constant A and the exponents B to E must be determined empirically.

A similar equation for droplet SMD of entrained sprays was formed, in which the relative air to liquid velocity was included in addition to those parameters appearing in Eq. (1):

$$SMD = f(L_1, L_2, \mu_f, \mu_g, \sigma, \rho_f, \rho_g, V_{fg}) \quad (3)$$

Again the hydraulic diameter of the channel does not have a direct influence on the droplet SMDs. Applying the Buckingham-PI analysis to Eq. (3) gives a correlation between dimensionless PI parameters as

$$\frac{SMD_1}{L_1} = A \left(\frac{L_1}{L_2} \right)^B \left(\frac{\rho_g V_{fg} L_1}{\mu_g} \right)^C \left(\frac{\rho_g V_{fg}^2 L_1}{\sigma} \right)^D \left(\frac{\mu_f}{\mu_g} \right)^E \left(\frac{\rho_f}{\rho_g} \right)^F \quad (4)$$

where the constant A and the exponents $B, C, D, E,$ and F must be determined experimentally.

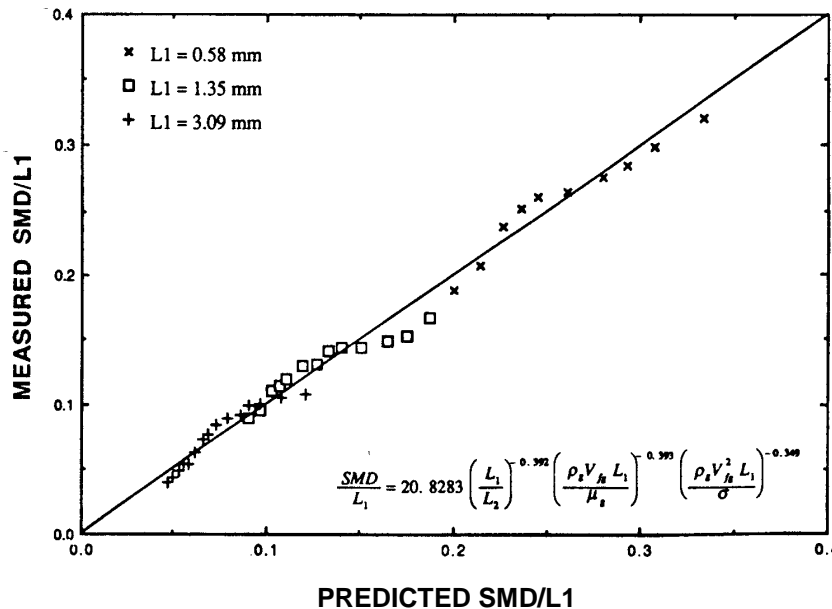


Fig. 5 Measured entrained spray droplet SMD / L, plotted against predicted values from the regressed correlation.

Results and Discussion

Onset Velocity for Entrainment

An experimental correlation between the critical Weber number and the viscosity group is presented for several different values of mesh length-to-height ratios in Fig. 4. Measured onset velocities for the three different meshes laid at the water-air interface were used to determine the constant and the exponents in Eq. (2) using a regression method. Since a single combination (water-air) for interface was considered, the viscosity and density ratios of the liquid and gas had to be implicitly included in the constant A . This resulted in an expression

$$\frac{\rho_g V_{fg}^2 L_1}{\sigma} = 0.254 \left(\frac{L_1}{L_2} \right)^{0.466} \left(\frac{\mu_g}{\sqrt{\rho_g \sigma L_1}} \right)^{-0.632} \quad (5)$$

where the critical We_{L1} decreases with decreasing L_1/L_2 ratios, when the viscosity group remains unchanged. A rough mesh with a large L_2 is expected to experience more nonuniform

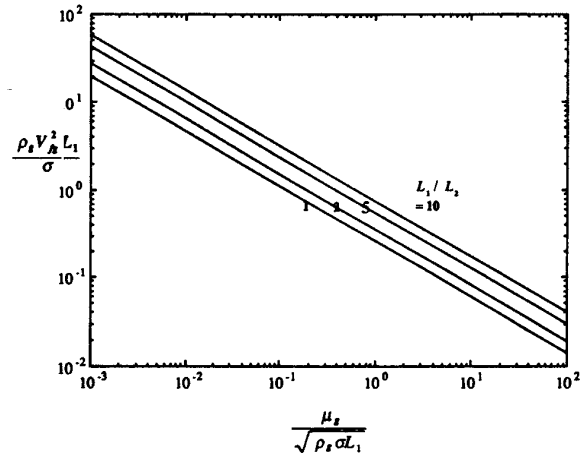


Fig. 4 Critical Weber number for the entrainment onset as a function of the dimensionless viscous group for different mesh length-to-height ratios.

pressure fluctuations because of the more corrugated interface causing the entrainment to occur at a lower critical velocity than a more flat-meshed interface. For a flat mesh with a relatively small value of L_1 / L_2 , the critical Weber number for entrainment will be higher. The viscosity group, $\mu_g / (\rho_g \sigma L_1)^{1/2}$, accounts for the viscosity shearing action from the gas flow over the holding action of the interface due to the surface tension. Since for higher viscosity groups, the shearing action overrides the holding action, and the critical Weber number decreases with increasing magnitude of the viscosity group and entrainment will readily occur.

Droplet SMD

For the case of water-air interfaces, the measured droplet SMDs were regressed into Eq. (4) and a comprehensive correlation between the dimensionless Sauter mean diameter, SMD/L_1 , and the other dimensionless parameters was determined:

$$\frac{SMD}{L_1} = 20.8283 \left(\frac{L_1}{L_2} \right)^{-0.392} \left(\frac{\rho_g V_{fg} L_1}{\mu_g} \right)^{-0.393} \left(\frac{\rho_g V_{fg}^2 L_1}{\sigma} \right)^{-0.349} \quad (6)$$

In this expression, the second and third terms on the right side represent Re_{L_1} , and We_{L_1} , based on L_1 . Again, the last two dimensionless parameters in Eq. (4) for liquid-to-gas density and viscosity ratios were excluded since the present study did not consider variations of these parameters. The correlation shows that SMD/L_1 increases with decreasing L_1/L_2 , Re_{L_1} , and We_{L_1} . The ratio of the entrained droplet SMD to a given L_1 , will be high for a rough mesh with a smaller value of L_1/L_2 , and will be low for a smoother mesh with a relatively large L_1/L_2 . High Re_{L_1} , and We_{L_1} , imply that the inertial impact forces are dominant when compared to the viscous and the surface tension forces, respectively, and result in entrainment under stronger convective action. The entrained droplet SMD, therefore, shows a decrease with increasing Re_{L_1} , and We_{L_1} . All the measured SMDs are plotted against the predicted values from the regression, Eq. (6), in Fig. 5. The data exhibited a good agreement with the regressed correlation with a maximum deviation of less than 10%.

Concluding Remarks

For the first time, two separate correlations for the entrainment onset velocity and the entrained droplet SMD were obtained from experimental data analyzed with the Buckingham-PI theorem. Saturated (or primed) mesh-laid interfaces between a water pool and a convective air stream was considered in an attempt to hydrodynamically simulate the entrainment phenomena in a heat pipe system. All the fluid properties were considered and/or evaluated at 1 atm and 20°C for the present case. If the results are applied to an operating heat pipe system at different temperatures, the constant A of both correlations must be modified in order to take into account the fluid property variations at the operational temperature of the individual heat pipes.

Acknowledgment

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