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ABSTRACT

A model has been created to describe the development of flow leaving a compressor as it transitions from mist to annular flow. Flow parameters such as the drop size, drop speed, drop concentration, film thickness, and film velocity change as a function of length. Parameters such as refrigerant flow rates, oil in circulation ratios, and fluid properties are accounted for in these models. While some flow development work is found in the open literature for air-water or steam-water flows, little work is available for air-conditioning applications. Due to the drastically different properties of refrigerant-oil mixtures from air-water mixtures, the existing models must be modified substantially for use in air-conditioning models. The existing models were modified using physical principles to incorporate the differences in fluid properties. The model closely approximates empirical results presented an accompanying paper.

1. INTRODUCTION

Adiabatic annular-mist flows occur in round tubes at relatively high qualities and vapor flow rates. These interactions eventually lead to a fully-developed flow regime after which the annular film reaches a constant time averaged value and the rate of deposition equals the rate of entrainment. Much of the work in deposition and entrainment has been focused on either extremely simple empirical models of fully developed tube flow or extremely fundamental studies of drop-film collision outcomes. While great physical insight may be gained from the fundamental studies, their applicability may be questionable. For example, Rein (1993) showed that single droplets striking a liquid surface were less likely to bounce than were droplets composing a stream. Work such as this makes it difficult to understand how fundamental drop-film collisions experiments can be applied to a real fluid stream.

Many authors have written papers describing individual interactions, which when combined, can be utilized to understand how annular-mist flows may change as they progress down a tube. For example, a great deal of work has been done in the field of droplet deposition to determine the relative importance of various fluid and flow parameters. In comparison to droplet flow development, far fewer works have been published on liquid film development. Far fewer works have been written explicitly on the parameters which affect overall flow development of parameters such as flow regime transitions, changes in void fraction, or the effect of non-uniformities in geometry. Most works focused on flow development have studied the effect of flow obstructions.

Salcudean *et al* (1983) showed that obstructions in center and periphery of tube cause earlier transitions to the fully developed flow regime than occurs when flow is in a tube with no obstructions. They believed that the mechanism which accelerated the regime transition was the randomizing effect of the obstructions. Taitel and Dukler (1987) responded to arguments concerning high viscosity fluids on the applicability of their more famous paper from 1976. They showed that pipe length was a critical parameter in determining the transition between stratified and non-stratified flow regimes for high viscosity fluids. Bowers *et al* (2006) studied liquid distribution in the header of a microchannel evaporator. They showed that the flow obstruction caused by further extending the microchannel tubes into the header led to higher velocities which promoted more homogenous flow. Ahmed *et al* (2008) studied flow development after an expansion. They showed that multiple flow regimes were seen at different lengths for air-oil flow. They found that the development length was a function of both the condition before expansion and area ratio of expansion. Bowers (2009) studied two phase flow development of R134a. Liquid R134a was passed through a valve to create a two-phase flow. Multiple regimes were seen along the tube as a function of length. Void fraction development as function of position was measured using a new image analysis technique.

2. EXPERIMENTAL DATA SET

The accompanying paper presents details on the experimental facility and how experiments were conducted. In brief, a full air-conditioning system was used to provide flow to an approximately 3 m long transparent perfluoroalkoxy (PFA) tube having an internal diameter of 6.35 mm. An automotive compressor was used for this experiment as the open shaft design and lack of an oil sump simplified the process of altering the compressor speed and oil circulation ratio, respectively.

Surface properties of the tube, such as wettability and roughness, will not match those of actually refrigeration lines. Wettability should not limit the application of the experimental results so long as the entire surface is coated by the liquid film. Likewise roughness effects should be minor so long as the film is laminar and the roughness is small compared to the film thickness.

The overall range of test conditions conducted as part of this research was for mass flow rates of 6.3 to 22 g/s, oil circulation ratios from 1.1 to 18.5%, discharge temperatures 44 to 103°C, discharge pressures from 1025 to 1375 kPa, liquid viscosities from 4 to 19 cP, and vapor densities from 26 to 54 kg/m^3. The entire data set may be found in Wujek (2011).

While the model created using this data set, as well as several of the other data sets from which earlier models were created, the curves and discussion will be focused on a single data set. The main reason for focusing on a single data set is to simplify the presentation of data and the subsequent discussion. The results from this specific condition were relatively typical and the model matches this data with a similar level of accuracy as to how well it fits the other data. The conditions measured in this discharge line were a temperature of 103° and a pressure of 1381 kPa. The mass flow rate was measured to be 21.2 g/s. At these conditions the bulk velocity of the vapor refrigerant is 12.5 m/s. The compressor frequency was determined based on readings from the frequency drive, motor information, and pulley ratio. From measured values, the oil circulation ratio was found to be 4.5%, meaning the oil flow rate was approximately 1.1 g/s. Liquid phase properties were determined using correlations developed by Seeton (2009).

4. DROP DEPOSITION MODELING

Droplets dispersed in the gas will eventually interact with the film to either deposit, bounce, or splash. One possible interaction is deposition, where droplets merge with the film. The basic form of drop deposition models is relatively simple. A deposition coefficient (k_d), is used to relate the liquid concentration (C) at two points (*1, 2*) located some distance apart (Δz) in a tube having a certain diameter (D) through which a vapor (g) having a density (ρ) and mass flux flows (G). The work of most researchers has been focused on updating the value of the deposition coefficient to fit their experimental or simulated results. The value of the deposition coefficient often takes many flow parameters into account.

$$k_D = \frac{\rho_g D}{4 G_g \Delta z} ln \frac{C_1}{C_2} \quad (1)$$

Among the earliest works describing droplet transfer to a wall was written by Alexander and Coldren (1951). Theoretical deposition correlations were developed, and experimentally validated, for droplet deposition in turbulent flow where the main resistance to deposition was due to lack of eddy diffusivity caused by semi-stagnant vapor near the wall. Also discussed was that droplet diffusion was an order of magnitude larger than gaseous diffusion. Their experiment showed that the region close to the wall has fewer droplets than toward the center of the tube. Davies (1965) described deposition of droplets by means of eddy diffusivity. By using the Nusselt number for material transport, which relates mass diffusivity to molecular diffusivity, he showed that high droplet transfer to the wall is only possible for thin boundary layers. In the boundary layer, the eddy diffusion coefficient decreases near to a point where only molecular diffusion becomes physically important. Farmer *et al* (1970) showed that the deposition constant increases with decreasing diameter for water droplets. Namie and Ueda (1972) experimentally studied the rate at which water droplets were transferred to the tube wall in an air-water annular-mist type flow. Droplet deposition constants were seen to increase with increasing gas eddy diffusivity and decreasing droplet concentration. Hutchinson, Hewitt, and Dukler (1971) devised a stochastic model for deposition of dispersed particles which relies on calculating the probabilities of random particle and eddy motions. The model simplifies the problem as being one dimensional in the radial direction by neglecting the fact that downstream and radial velocities are generally coupled. A summary of a wide range of experimental deposition works was made by McCoy and Hanratty (1977). They divided the research into horizontal and vertical flows and classified the experiments by the method by which droplets were produced and how the results were measured. Particles were either injected, originated from the wall, or from a fully developed annular film. The vertical flow experiments considered included the deposition of water, metal particles, and pollens in both upward and downward flow configurations. Gravitational settling was shown to control the settling process for vertical deposition constants an order of magnitude less than the terminal velocity; whereas gravitational settling can be neglected when the orders of magnitude are reversed. Hay, Liu, and Hanratty (1996) measured drop size distribution and related size to deposition and concentration in air-water flow. They cited the argument from Binder and Hanratty (1991) that the deposition rate is proportional to the root-mean-square of the turbulent velocity fluctuations. At small droplet concentrations the rate of deposition grows linearly with flow rate of entrained droplets. Droplet flux was measured as a function of radial position; a sharp increase in droplet flux near the wall was found. The gas velocity profile was shown to become more parabolic for higher liquid flow rates due to increased shear stress near the wall caused by increasingly rough film surfaces. Soldati and Andreussi (1996) expanded on their previous work to take into account the effect of droplet coalescence on deposition rate. Starting from fundamentals, they argued that droplet-droplet collisions are more likely to increase the time it takes for large droplets to reach the wall due to inelastic collisions diverting the droplets away from the walls. Their model, which had empirical constants, had good agreement with both their high and low liquid flow rate experiments. Okawa and Kataoka (2005) experimentally studied droplet deposition and entrainment in upward annular flow. Deposition mass transfer coefficients were shown to increase with increasing gas mass flux and decrease with increasing droplet concentration. Simple correlations were given for deposition at high and low droplet concentrations. High mass concentrations are those where droplet-droplet interactions become common which decreases the deposition constant. Jeppson, Azzopardi, and Whalley (1989) showed that the deposition coefficients were larger at higher gas velocities and lower gas densities. Low gas velocities preferentially deposit larger droplets because large droplets are not deposited by eddy diffusivity. Hewitt and Govan (1990) presented droplet deposition data for air-water, fluoroheptane, air-genklene, and steam water flows over a range of droplet densities. Correlations were developed for high and low droplet densities of entrained droplets. Low and high droplet densities were separated by an overall droplet density being 1/3 the gas density. Sugawara (1990) built on the mass transfer analogy by including a droplet concentration parameter to predict the deposition mass transfer coefficient.

The main concern with the deposition models is that water has been used as the liquid in developing almost all correlations for deposition. Most mathematical models are based on the assumption that droplets which reach the tube or film surface are deposited, or at least that a certain fraction of drops deposit. Several authors have shown that the Weber number controls the probability of a droplet depositing on a liquid film. Cossali, Coghe, and Marengo (1997), Hewitt and Govan (1990), Jepson *et al* (1989), and Pan and Law (2007) have all demonstrated correspondence between Weber number and deposition. For example, Pan and Law (2007) extensively studied droplet-film interactions experimentally and numerically to defined a regime map for droplets colliding with a film consisting of four outcomes: permanent merging with minimal droplet deformation, bouncing, permanent merging after substantial droplet deformation, and merging followed by separation and formation of secondary droplets. The boundary between bouncing and absorption regimes as a function of Weber number and normalized film thickness is shown in Figure 1. From the diagrams presented in the paper, it can be seen that the droplets are more likely to be absorbed when the surface tension is small (generally We>15), and the film is either an order of magnitude thinner or about the same thickness as the droplet diameter.

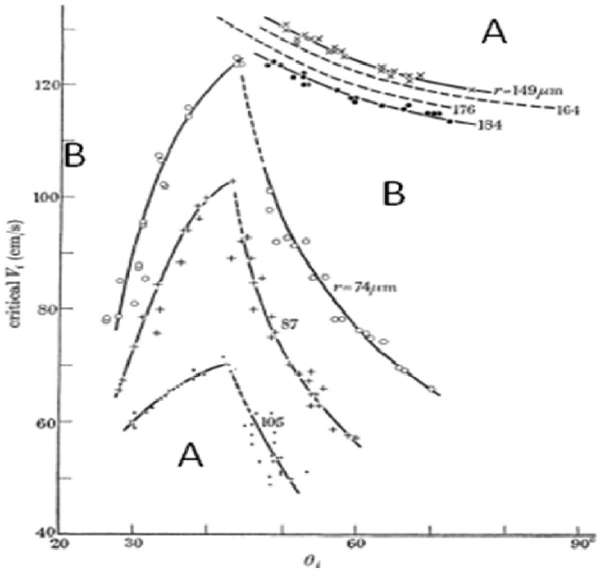

Figure 1: Collision outcomes for droplets of different diameters striking a liquid film Pan and Law (2007)

However, all of the fundamental drop collision outcome research has produced discrete impact regimes of coalescing and bouncing. To understand probabilities for each outcome a different approach was taken. Because steady state experiments in the literature are generally created using methods where drops are allowed to interact with the surface, the fully developed entrainment fraction provides clues on the probability of droplet deposition. Starting from the dependence found by Ishii and Mishima (1989) for fully entrained droplet fraction, a Taylor series expansion for hyperbolic tangent was used to approximate the dependence on fully developed entrained mass fraction. If there is no entrainment, the deposition constant is inversely proportional to entrained mass fraction. Therefore the deposition constant for correlations based only on water can be adapted for other fluids by Equation 2. In this expansion, only the liquid phase Weber number (*We*) is necessary to expand the application of deposition models developed for water to other fluids. For this test condition, the deposition constant is reduced by a factor of 4.08 compared to the deposition constant determined using models developed for steam-water flows.

$$k_D = k_{D,water}\left[\left(\frac{We}{We_{water}}\right)^{1.25} - \frac{\left(\frac{We}{We_{water}}\right)^{3.75}}{3} + \frac{2\left(\frac{We}{We_{water}}\right)^{6.25}}{15}\dots\right] \tag{2}$$

4. DROP ENTRAINMENT MODELING

In 1940, Taylor (1963) mathematically studied the enlargement of liquid waves caused by gas flow over the surface; this wave growth is generally referred to as the Rayleigh-Taylor instability. It was predicted when the waves grow sufficiently large, drops may detach form the wave crests. Predictions of the wave length would be roughly equal to droplet size were combined with the growth rate equations to predict the rate of entrainment. Entrainment flow rate was predicted to be proportional to gas velocity and the square root of the density ratios. The analysis of Taylor was later shown to be flawed for thin liquid layers by Tatterson (1977). Some of the earliest work discussing oil entrainment in gas flow was done by Van Rossum (1959), who studied flows of air with a variety of liquids in a 15 cm square duct. While part of the work was focused on film thickness and flow rate measurements, this was done as a prelude to entrainment analysis. It was shown that atomization (or entrainment) occurred at higher gas flow rates than are required for wave formation. Thin, less than 1mm, water films were found to be more easily atomized than oil; however the reverse was true for thick films. For large ratios of velocity multiplied by viscosity to surface tension, the critical gas Weber number for entrainment approached 17 for a wide variety of fluids. A graphical correlation, which may be seen in Figure 5-8, was fit to the data for gas velocities greater than 25 m/s. A rule of thumb was given that the minimum vapor flow velocity for entrainment in meters per second was approximately ¼ the surface tension given in dynes per centimeter. Woodmansee and Hanratty (1969) used high speed photography, of up to 5000 frames per second, to study how droplets were formed by air flowing over a liquid film. At high liquid flow rates, predominantly two-dimensional roll waves were shown to occur at lower gas velocities than required for droplet entrainment. The droplets were formed from small ripples growing by Kelvin-Helmholtz instability which were superimposed on the front of the roll waves. Film thickness was relatively insensitive to liquid flow rate for a fixed gas flow rate. At low liquid flow rates, entrainment caused dry-out before roll waves could occur. Ishii and Grolmes (1975) developed physical correlations for entrainment in three different flow regimes: transition, rough turbulent and low Reynolds number. The most common entrainment method at high gas flow rates is caused by shear forces acting at the top of a roll wave. The authors showed the minimum liquid Reynolds number required for entrainment was a function of gas density, with low density gas requiring thicker film.

Tatterson (1975) studied the rates of entrainment in horizontal air-water flow. Atomization was shown to increase as a function of the Weber number multiplied by the square root of the film height divided by diameter for a fully developed annular regime for gas velocities greater than 40 ft/s, for large viscosity groups, and with tube diameters 3/8 to 5 1/2 inches. Tatterson, Dallman, and Hanratty (1977) used Kelvin-Helmholtz instability analysis as the basis for a theoretical description of how droplets are formed in annular flows. The basic stages in the droplet formation mechanism are shown in Figure 3. Dallman, Laurinat, and Hanratty (1984) presented equations for predicting the fully developed entrained mass fraction in horizontal tubes. The form of one of the equations for entrainment rate, shown in Equation 3, was based on equating existing, empirical rate equations for entrainment and deposition in fully developed flows. It relates entraiment rate (ε) to tube diameter (D_t) and perimeter (P), liquid viscosity (μ_f), film flow rate (m_f), gas phase Weber number (We_g), and the densities (ρ) of both fluid phases. At gas velocities below the critical gas velocity, which is expressed in the 0.046P term, no entrainment occurs. Shadel, Leman, Binder, and Hanratty (1990) showed a linear increase in atomization rates with regard to excess film flow rate in tubes with inner diameters between 2.54 and 5.715 cm. Excess film flow rate is the difference in film flow rate from the critical film flow rate for entrainment. As an example 2.54 cm tube data is shown in Figure 4. The mass transfer coefficient was seen to be independent of pipe diameter and gas velocity. Hewitt and Govan (1990) presented a new annular flow model which determined the entrainment rate above the critical film flow rate above which entrainment could occur. Above the critical liquid flow rate, the entrainment constant remains steady until the liquid mass concentration in the core is 0.3 where it linearly decreases with concentration. Bertodano, Assad, and Beus (2001) compared three major groups of entrainment correlations which were originally put forward by Dallman et al (1979), Katoaka and Ishii (1982), and Taylor (1963). The model by Katoaka and Ishii were shown to have the same scaling of key variables as Taylor. When attempting to plot R113 data using the form of Dallman, it was shown that the functional dependence was correct, but magnitudes of entrainment were off substantially since this correlation was developed for air-water. The Kataoka correlation performed poorly when extrapolated, due to the wrong Reynolds number dependence. Okawa and Kataoka (2005) showed interfacial shear and surface tension scaled with the entrainment rate for a variety of air-water and steam-water studies. A similar relationship between entrainment and surface tension was shown by Mori *et al* (2007).

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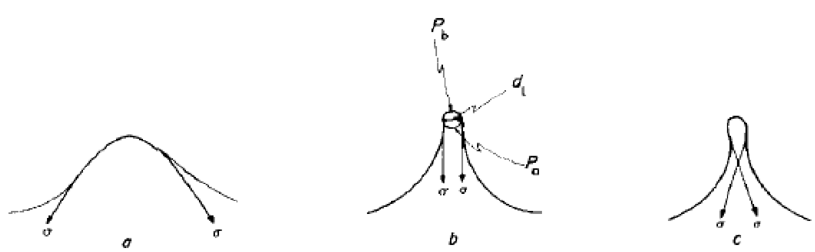

Figure 3: Tatterson, Dallman, and Hanratty (1977) Kelvin-Helmholtz mechanism for droplet formation

$$\frac{\varepsilon D_t}{\mu_f} = \frac{3.5\times10^{-6}}{4}\left(\dot{m}_f - 0.046P\right)We_g\sqrt{\frac{\rho_f}{\rho_g}} \tag{3}$$

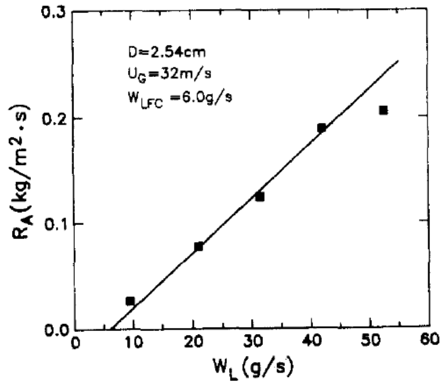

Figure 4: Shadel, Leman, Binder, and Hanratty (1990) Rate of atomization as a function of excess liquid flow rate

Instability growth at the crest of dispersion waves is cause of entrained drops. Dallman, et al (1984) demonstrated the form the entrainment equation would take when a critical film thickness is requisite for entrainment to occur. As Dallman presented an empirical correlation which worked with water, again it is necessary to modify the correlation to account for changes in fluid properties. Here, the analysis of Taylor (1963) on the generation of dispersion waves is used to modify the critical liquid film mass flow rate. Taylor mathematically showed that the growth rate of the fastest growing wave. As the fastest growing waves are those which form dispersion waves, Dallman's equation should be modified as shown in Equation 4 to reflect the change in surface tension which was not incorporated into Dallman's model. This rationale of this modification is that lower surface tension will cause entrainment to occur at lower liquid flow rates and will cause faster growth in dispersion waves. Coincidentally, Bertodano, Assad, and Beus (2000) showed similar relationships for the entrainment constant in connecting entrainment rates of air-water to R113 systems, but did not take the final step of properly scaling the equation to be used with other fluid flows. As an effect of how this scaling was incorporated, the equation perfectly overlays both the Dallman *et al* and Bertodano *et al* models. Therefore this model matches the previous data sets, as well as the refrigerant-oil data sets which can be found in Wujek (2011).

$$\frac{\varepsilon D_t}{\mu_f}=\frac{3.5\times10^{-6}}{4}\left(\frac{We}{We_{water}}\right)\left(\dot{m}_f-0.046P\sqrt{\frac{We}{We_{water}}}\right)We_g\sqrt{\frac{\rho_f}{\rho_g}} \tag{4}$$

4. COMBINED DEPOSITION AND ENTRAINMENT MODELING WITH COMPARISON TO EMPIRICAL RESULTS

By knowing the initial flow conditions and by combining the models deposition models with an entrainment model it is possible to model the amount of liquid flow contained in the mist and the film phases. The initial conditions for the data set to be discussed in this section can be found in the accompanying paper. Initially the flow is considered to be completely contained in the droplets, after some distance a liquid film starts to develop. If the liquid film reaches a critical thickness drops will be entrained from the film.

To show the effect of not properly accounting for the fluid properties, the models are applied without the new compensation techniques presented in this paper. Several deposition models were used along with the Dallman *et al* (1979) entrainment model to create the plot shown in Figure 5. The experimental data set presented in the accompanying paper can be seen in the same plot. The mass flow rates are converted from the concentration values required in the model. By comparing the model to the results, it can be seen that there is poor agreement between any of these models and the experimental results passed the first 0.5 meters. During the first section of the tube, some of the models roughly approximate the measured concentration. One reason why the models seem to closely approximate the values near the beginning but fail at later positions could be due to the relative importance of entrainment. Because the original models were made for water as the liquid, the critical values for entrainment are such that no entrainment is predicted for the oil flow rates found in this experiment.

Next, the deposition constant is modified by Equation 2 while the entrainment model is modified by Equation 4. The results of applying these corrections for fluid properties can be seen in Figure 6. Now the models appear to relatively closely predict both the values and the trends found in the example data set to within the accuracy of the experimental results. It can be seen that these corrections make the more recent and robust models of Govan, Hewitt, and Ngan (1988) and of Lee, Hanratty, and Adrian (1989) very good estimators of drop concentration at downstream positions. These models however do not appropriately capture the deposition at the beginning of the tube. The models from Leman *et al* (1985), Cousins and Hewitt (1968), Andreussi and Azzopardi (1983), and Bennett *et al* (1966), all seem to be in much closer agreement with the data near the beginning of the tube. The changes in the modeled drop mass flow curves are most noticeably closer at longer development lengths. This is because of modifications made to the entrainment models. As the film thickness is negligible at the beginning of the tube, droplet entrainment does not occur in a meaningful fashion until after the critical liquid film flow is achieved. With some models, the beginnings of a fully-developed flow regime have already appeared, in any case, the fully developed mass flow in the droplets will be substantially greater than when fluid properties were not accounted for.

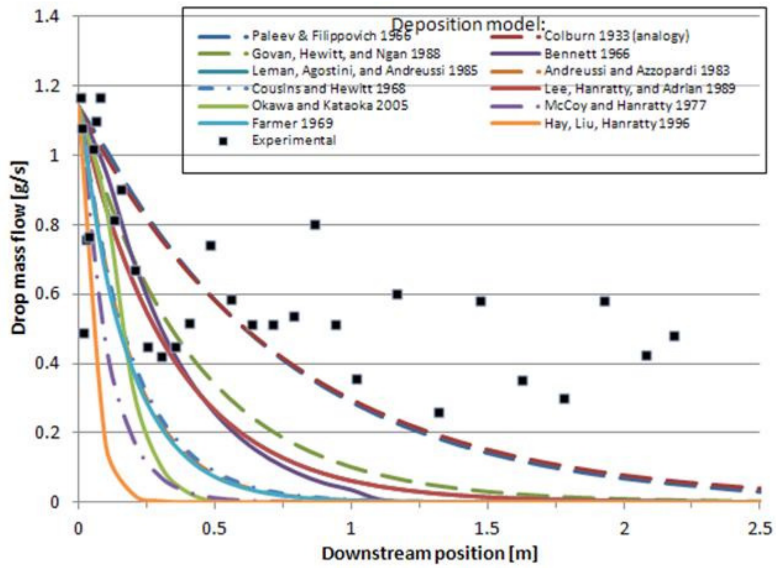

Figure 5: Comparison of drop mass flow rate development experimental values to models which had not been adjusted based on fluid properties

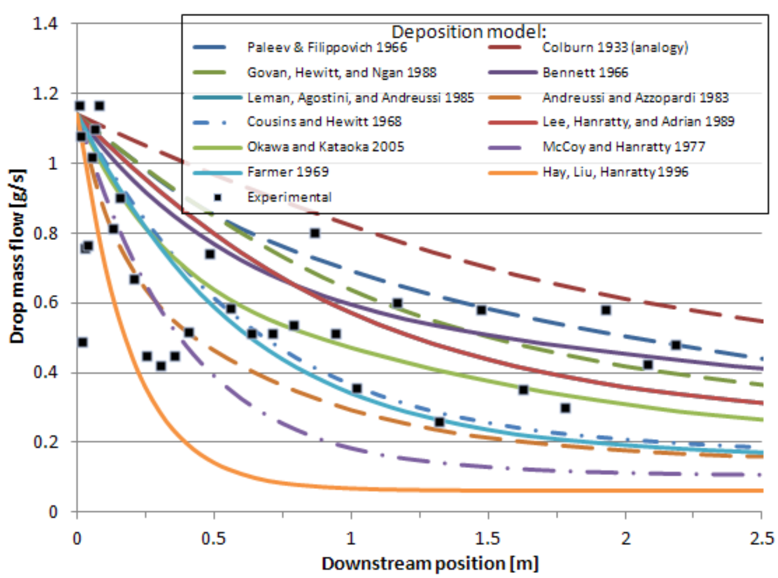

Figure 6: Comparison of drop mass flow rate development experimental values to models adjusted based on fundamentals to incorporate fluid properties

The total liquid flow rate, in these experiments is given by the initial liquid drop flow rate. From drop concentration measurement and drop entrainment and deposition models, it is possible to model the flow rate of the liquid film. This continuity based approach relates that where the liquid flow which is no longer in the drops must now be in the film. The results of this model are shown in Figure 7. The results of these curves can be compared to the experimental data found in the accompanying paper.

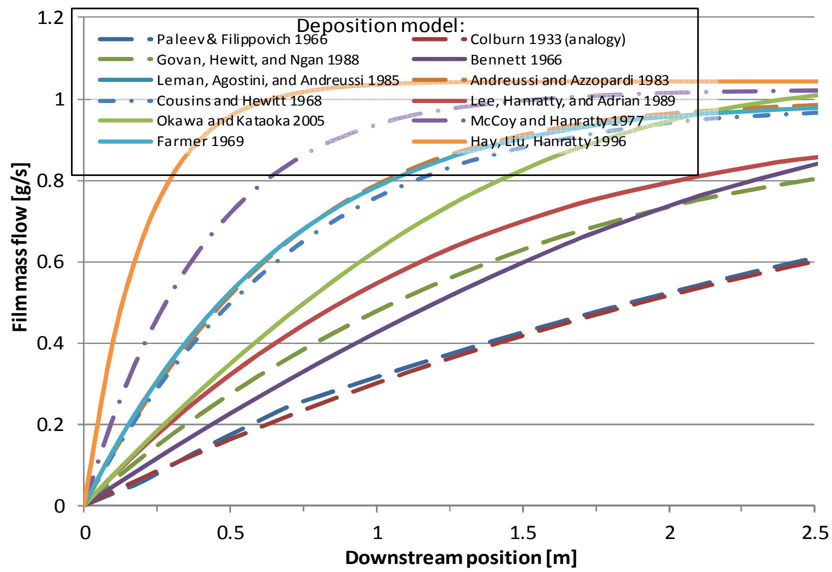

Figure 7: Film mass flow development modeled directly from entrainment and deposition models

The models not only do a far better job of matching the experimental results at the single test condition, but also for all experimental data found in Wujek (2011). The percent absolute mean deviation from the experimental results for each data set at each downstream position can be found in Table 1. It can be seen that now any deposition model can be used to an accuracy of about 25% over a wide range of conditions so long as the fluid properties are accounted for. It should be noted that the uncertainty in experimental data is quite large, and in general the model appears similar to a curve fit of the data when plotted on the same set of axis. Because the data set was really an addition to the large data sets used to create the steam-water models, it is believed that this model could be applicable over a wide range of conditions: diameters greater than 6.35 mm, liquid viscosities from 0.001 to 0.19 Ns/m^2, surface tensions from 0.025 to 0.075 N/m, and vapor densities from 1.2 to 54 kg/m^3.

Table 1: Percent absolute mean deviation of model to entire experimental data set

Deposition model	Drop flow rate	Film flow rate
Paleev & Filippovich 1966	23.5	13.5
Colburn 1933 (analogy)	23.6	12.6
Govan, Hewitt, and Ngan 1988	28.9	12.9
Bennett 1966	27.0	11.8
Leman, Agostini, and Andreussi 1985	25.1	14.4
Andreussi and Azzopardi 1983	30.6	21.5
Cousins and Hewitt 1968	29.7	20.3
Lee, Hanratty, and Adrian 1989	25.1	14.4
Okawa and Kataoka 2005	33.1	17.6
McCoy and Hanratty 1977	32.1	26.1
Farmer 1969	31.4	21.5
Hay, Liu, Hanratty 1996	38.8	38.3

5. CONCLUSIONS

Drop entrainment and deposition models which were originally developed for air-water, steam-water, or pure R113 flows have been modified to account for the dramatically different properties of refrigerant oil mixtures. By relating the fundamental work of other researchers regarding the impact of fluid properties on collision outcomes and wave growth, it was possible to create a model which fits not only the data set presented in the accompanying paper, but also the large library of data from which the original models were created.

Because existing models were simply scaled to account for fluid properties, the existing models can be applied to a new set of fluids with only slight modifications necessary to account for the change in fluid properties. The most important of these properties in this instance seems to be surface tension. The surface tension of this liquid, oil saturated with refrigerant, is approximately 1/3 the surface tension of the liquid the correlations were originally made for: water.

The main modification to drop deposition models was to account for the Weber number of the liquid in comparison to the Weber number of water. For drop entrainment models, the main difference comes from recalculating the critical mass flow (or Reynolds number) for entrainment and scaling the liquid phase Weber number to reflect the underlying physical instability which causes entrainment. In summary, the deposition constant and the entrainment equation should be modified as shown:

$$k_D = k_{D,water}\left[\left(\frac{We}{We_{water}}\right)^{1.25} - \frac{\left(\frac{We}{We_{water}}\right)^{3.75}}{3} + \frac{2\left(\frac{We}{We_{water}}\right)^{6.25}}{15} \ldots\right] \qquad (2)$$

$$\frac{\varepsilon D_t}{\mu_f} = \frac{3.5\times10^{-6}}{4}\left(\frac{We}{We_{water}}\right)\left(\dot{m}_f - 0.046P\sqrt{\frac{We}{We_{water}}}\right)We_g\sqrt{\frac{\rho_f}{\rho_g}} \qquad (4)$$

When the model was applied to the entire collection of flow development data found in Wujek (2011), drop flow rates and film flow rates could be successfully modeled to within a 25% absolute mean difference. It was shown graphically that the new model captures the general trend of the data in a manner which the models developed for steam-water flows were incapable.

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