A GENERALIZED CORRELATION FOR STEAM CONDENSATION RATES IN THE PRESENCE OF AIR-HELIUM MIXTURES

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ABSTRACT

Steam condensation in the presence of light noncondensable gases is critical in many nuclear plant safety applications, not the least of which are hypothetical severe accidents where H_2 is present in addition to the containment air inventory. Investigators have used helium as a surrogate for H_2, and have proposed a number of correlations and/or databases to estimate steam condensation rates in the presence of air-helium mixtures under free convection regimes typical of reactor flows. These studies are purely empirical, and hence do not allow to draw clear dependencies of the heat transfer rate on critical thermal-hydraulic parameters. In this study, we do away with the particular forms of the correlations, and go back to the original experimental data, consolidate them in a single database, and propose a generalized correlation that is compatible with the heat and mass transfer analogy. This best-estimate correlation for steam-air-helium mixtures, based on four different investigations and 180 data points, covers ranges of conditions expected under severe accidents. The consolidated raw data gather around a curve with a standard deviation of 20 %, which is within typical experimental error bands.

KEYWORDS
Film condensation, Air-Helium gases, Correlation, Nuclear plant safety

1. INTRODUCTION

Vapor film condensation is a topic of considerable importance in a variety of nuclear Light Water Reactor (LWR) safety applications. In many instances, vapor condensation takes place in the presence of some amounts of noncondensable (NC) gases, typically air or nitrogen, and sometimes hydrogen if the transient scenario progresses into a severe accident. The main concern has always been that small amounts of NC gases result in large decreases in steam condensation rates. The early experiments by Al Diwani and Rose [1] highlighted the fact that condensation rates can be degraded by as much as 50% with a NC gas content of no more than one percent by mass in laminar free convection regimes.

Many analyses, e.g. Sparrow and Minkowycz [2] and Rose [3], have provided theoretical explanations of this great reduction in heat transfer by even tiny amounts of NC gas. Solving boundary layer equations for the steam-NC mixtures, the authors showed that a diffusion boundary layer is formed, whereby the NC gas accumulates near the gas-condensate film interface, considerably lowering the steam partial pressure, and hence condensation rate. The deterioration in heat transfer is more pronounced for free convection flows than it is for forced flows.

A large body of experiments on the condensation degradation by NC gases has been produced over the years to cover a variety of conditions of interest to nuclear safety. The earliest such work is due to Uchida et al. [4] who proposed a simple correlation for the heat transfer coefficient (HTC) in free convection regimes typical of LWR containment flows. The Uchida correlation is used until today in safety

simulation codes, and is generally regarded as conservative for design basis accidents (DBA). Following this early work, a number of correlations have been developed to estimate the condensation HTC in the presence of NC gases at pressures of less than 6 bars. To name a few works of interest, one should mention the experiments by Dehbi et al. [5], Kataoka et al. [6], Anderson et al. [7] and Liu et al. [8].

Most of the works to date have involved the use of a single NC gas, e.g. air or nitrogen. In case of a severe accident, however, H_2 may also be present in the mixture. A handful of experimental investigations have addressed the presence of a light gas in addition to air, for example Dehbi et al. [5], Anderson et al. [7], Liu et al. [8], and most recently Su et al. [9, 10], and all of which having used helium as a surrogate for H_2 for obvious safety concerns. The available correlations have in common the fact that they are largely empirical fits of the data. In many instances, these correlations give different dependencies of the HTC on critical parameters. For example, the Dehbi et al. correlation [5] stipulates that the HTC varies inversely with the degree of wall subcooling to the power 1/4, as in the Nusselt formulation for pure vapor condensation. On the other hand, the Su correlation [9, 10] gives a power of 0.35 to 0.6, depending on the range of subcooling. These apparent contradictory predictions can be traced back to the purely empirical way in which experimental data have been correlated.

When dealing with steam-air-hydrogen mixtures, analysts often employ conservative correlations (e.g. Uchida) based on steam-air data, and simply replace the volume of H_2 by an equal volume of air to estimate the vapor condensation rate. In severe accidents scenarios, however, the use of conservative correlations is not warranted because they imply a larger steam content, hence a larger-than-actual dilution of hydrogen. A conservative assumption in DBA can turn into a non-conservative hypothesis in severe accidents.

It is therefore concluded that for best-estimate simulations, one should use a correlation which is based upon physical grounds, and which spans a wide range of conditions. In this investigation, we aim at proposing such a correlation that makes use of a large data set assembled by various investigators in the last decades. We will disregard the particular correlations, go back to their original underlying data, and consolidate them to produce a unified, best-estimate correlation. The way to achieve the form of this generalized correlation will be based on theoretical models, in particular the heat and mass transfer analogy (HMTA).

2. THE EXPERIMENTAL DATASETS

Four data sets on filmwise steam condensation over vertical surfaces in the presence of air-helium mixtures have been selected for inclusion in the new correlation. The chosen datasets consist of tests by Dehbi et al. [5], Anderson et al. [7], Liu et al. [8] and Su et al. [9,10]. These tests are typical of the turbulent, free convection regimes that characterize long-term containment flows. The selected works provide representative data collected over the past two decades and consist of a total of 180 data points. The ranges of experimental parameters are displayed in Table 1. Detailed information on the selected tests is given in their respective references or in summary form in the recent paper by Dehbi [11].

Table I. Range of experimental conditions

Experiment	Steam mass fraction	Helium volume fraction	Pressure	Wall subcooling	HTC	Number of data points	Experimental error in the HTC
	-	-	bar	K	W/m^{2}K	-	%
Dehbi (1991)	0.10-0.72	0.09-0.38	2.9-3.3	25-40	120-640	74	15
Anderson (1998)	0.12-0.63	0.03-0.38	1.0-3.0	15-60	60-680	49	10
Liu (2000)	0.29-0.81	0.04-0.19	2.5-4.5	5-30	290-1600	14	13
Su (2013, 2014)	0.40-0.93	0.03-0.15	2.0-5.0	20-70	280-1500	41	15

3. CONDENSATION RATE FROM THE HEAT AND MASS TRANSFER ANALOGY

3.1 Model set-up

A more physically based way of correlating data must be used in order to produce a formulation that is both general and of best-estimate nature. We will use the HMTA to deduce the dependency of the HTC on a selected number of physical parameters.   We assume hereafter that the vapor phase contains an ideal mixture composed of two NC gases and water vapor, and that the liquid phase consists of water. In addition, local thermodynamic equilibrium is assumed to prevail at the liquid-vapor interface, and only film condensation is considered.

When a steam-air-helium mixture is in contact with a cold flat condenser surface, a diffusion layer develops as shown in Figure 1. Under condensing conditions, the steam volume (mole) fraction at the wall is equal to the ratio of the vapor partial pressure at the liquid-gas interface temperature T_i divided by the total pressure. Hence the steam mole fraction at the interface is reduced compared to the bulk value. On the other hand, since the total pressure P is constant over the diffusion layer, the partial pressures of air (P_{air}) and helium (P_{he}) increase as the gas-liquid condensate interface is approached, causing a degradation of the condensation rate. Because of its high diffusivity, the helium partial pressure is expected to vary only mildly over the boundary layer. The steam mass fraction W_s is defined as the ratio of steam to total mixture density:

$$W_s \equiv \frac{\rho_s}{\rho} = \frac{\rho_s}{\rho_s + \rho_{nc}} = \frac{\rho_s}{\rho_s + \rho_{air} + \rho_{air}} \tag{1}$$

In the absence of radiation, three heat transfer modes are present: vapor condensation at the interface, sensible convection heat transfer from the bulk to the interface, and conduction through the liquid condensate. In steady state one can write:

$$h_f (T_i - T_w) = (h_{cd} + h_{cv})(T_\infty - T_i) \tag{2}$$

h_f is the liquid film conduction HTC, h_{cd} and h_{cv} are respectively the condensation and convection HTCs between the gas bulk and the gas-liquid interface. The total HTC can then be written as:

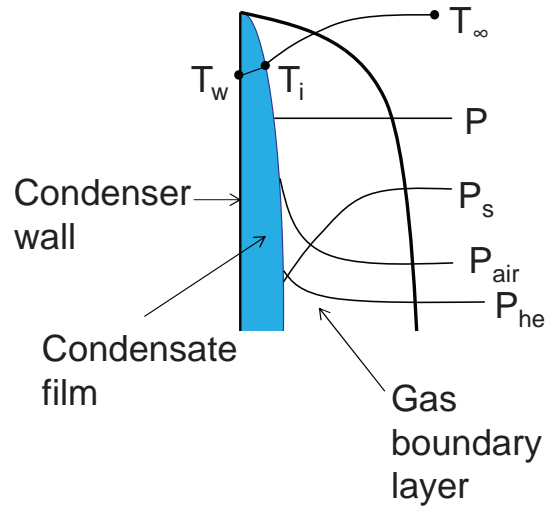$$h = \frac{1}{\dfrac{1}{h_{cd} + h_{cv}} + \dfrac{1}{h_f}} \tag{3}$$

Figure 1: Schematic of the diffusion boundary layer

If the NC mass fraction is relatively large (greater than 0.1), the film resistance can be neglected, and the interface temperature can be approximated with the wall temperature. This will be the case hereafter in this work. Thus the effective HTC is computed as:

$$h = h_{cd} + h_{cv} \tag{4}$$

The condensation rate is governed by the rate of diffusion of water vapor towards the cold surface. Species mass fluxes for the NC gas mixture (air-helium) and water vapor at the liquid vapor interface include both convective and diffusive components. Hence, following the formulation of Bird et al. [12], one can write the species mass fluxes in the boundary layer as follows:

$$\dot{m}''_{nc} = \rho W_{nc} v - \rho D \frac{\partial W_{nc}}{\partial n} \tag{5}$$

$$\dot{m}''_{s} = \rho W_{s} v - \rho D \frac{\partial W_{s}}{\partial n} \tag{6}$$

In the above v represents the mixture velocity, D the effective mass diffusion coefficient, and n the normal direction to the wall (liquid film). The subscripts *nc* and *s* refer to the total NC mixture and steam, respectively. Using the fact that the mass fractions of the mixture add up to unity, the mixture mass flux at the wall $\dot{m}''_w$ can be written as:

$$\dot{m}''_{w} = \dot{m}''_{nc, w} + \dot{m}''_{s, w} = (\rho v)_{w} \tag{7}$$

We impose in addition the condition that the interface is impermeable to the NC gas mixture:

$$\dot{m}''_{nc, w} = 0 \tag{8}$$

The mass flux of vapor condensing at the wall is thus:

$$\dot{m}''_{s, w} = \frac{- \rho D \dfrac{\partial W_{s,w}}{\partial n}}{1 - W_{s,w}} \tag{9}$$

The condensation mass flux can also be expressed as a function of the mass transfer coefficient h_m:

$$\dot{m}''_{s,w} = \frac{-\rho D \frac{\partial W_{s,w}}{\partial n}}{1-W_{s,w}} = h_m \frac{W_{s,\infty}-W_{s,w}}{1-W_{s,w}} = \frac{\rho D \cdot Sh_o}{L} \cdot \frac{W_{s,\infty}-W_{s,w}}{1-W_{s,w}} \tag{10}$$

In the above, Sh_o is the Sherwood number for low mass transfer rates, and the subscript ∞ refers to bulk conditions. Invoking the HMTA and assuming the gas mixture flow is turbulent and naturally driven, one can express the Sherwood number according to a form analogous to the McAdams correlation for free convective flows:

$$Sh_o = \frac{h_m L}{\rho D} = 0.13 \cdot (Gr \cdot Sc)^{\frac{1}{3}} \tag{11}$$

Gr refers to the Grashof number and Sc the Schmidt number. Since considerable variations of densities occur in the diffusion boundary layer, the Grashof number is defined in terms of density differences rather than temperatures, that is:

$$Gr = \rho g \frac{\rho_w - \rho_\infty}{\mu^2} L^3 \tag{12}$$

The Schmidt number is defined as:

$$Sc = \frac{\mu}{\rho D} \tag{13}$$

In the above expressions, g is the gravity acceleration and μ the mixture viscosity. One notes that according to (11), the mass transfer coefficient h_m (and hence condensation HTC) is independent of length scales, as is the case in turbulent free convection flows. The binary diffusion coefficients of air in steam and helium in steam are computed following the formulation of Wilke and Lee [13]. The evaluation of the effective mixture diffusion coefficient D is addressed in Section 4. The mixture viscosity is computed according to the method of Wilke [14]. The mixture density can be obtained assuming the ideal gas law:

$$\rho = \frac{P \cdot M}{R \cdot T} \tag{14}$$

where R is the universal gas constant, T the temperature, and M the effective mixture molecular weight computed as a function of the species mass fractions as follows:

$$M = \left[\frac{W_s}{M_s} + \frac{W_{air}}{M_{air}} + \frac{W_{he}}{M_{he}} \right]^{-1} \tag{15}$$

3.2 Suction Effect

The equations developed so far allow one to compute the vapor mass flux and hence total heat transfer coefficient, provided the steam mass fraction at the interface is known. In reality, the mass transfer induces a suction effect at the gas-liquid interface, leading to shaper concentrations gradients, and ultimately heat and mass transfer rates that are larger than those implied by the HMTA at low mass transfer rates. The enhancement in the mass transfer rate has been quantified by a number of authors for specific conditions. The most common expression for the correction factor that needs to be applied to the HMTA mass transfer rate is the logarithmic form derived by Bird et al. [12]:

$$\Theta = \frac{\ln(1+B)}{B} \tag{16}$$

The suction parameter B is defined as:

$$B \equiv \frac{W_{s,w} - W_{s,\infty}}{1 - W_{s,w}} \tag{17}$$

The Bird correction factor Θ has been developed based on the stagnant film theory (Couette flow) which assumes that the radial fluid velocity toward the wall is zero and only diffusion is active in that direction. It has been experimentally verified by Moffat and Kays [15] for low turbulence forced single phase flows over a flat plate, at conditions which are far removed from the naturally driven flows considered in this study. De la Rosa et al. [16] argue that in the turbulent regime, the simple stagnant film assumptions are no longer compatible with the laws of the wall, hence deviations from the data occur and get larger as the wall normal velocity (condensation rates) increases.

Given that we intend to provide a generalized correlation for a wide range of available experimental tests, we assume the suction effect is embedded in the free parameter ϕ which will be estimated from the best fit of the complete data set. We will nevertheless assume that for a fixed NC gas mixture, ϕ depends solely on the Bird factor Θ:

$$\phi = f(\Theta) \tag{18}$$

The HMTA formulation for the enhanced condensation rate can therefore be expressed as:

$$Sh = \phi \cdot Sh_o = \phi \cdot 0.13 \cdot (Gr \cdot Sc)^{\frac{1}{3}} \tag{19}$$

Thus:

$$\dot{m}''_{s,w} = \phi \cdot \frac{\rho D \cdot Sh_o}{L} \cdot \frac{W_{s,\infty} - W_{s,w}}{1 - W_{s,w}} = \frac{h_{cd}(T_\infty - T_w)}{h_{fg}} \tag{20}$$

where h_{fg} is the vapor latent heat. The condensation HTC can thus be written as:

$$h_{cd} = \phi \cdot \frac{0.13 \cdot \rho D \cdot (Gr \cdot Sc)^{\frac{1}{3}}}{L} \cdot \frac{W_{s,\infty} - W_{s,w}}{1 - W_{s,w}} \frac{h_{fg}}{(T_\infty - T_w)} \tag{21}$$

The approach is simplified even further by also incorporating the small effect of convective heat transfer (usually a few percent) in the free parameter ϕ to be determined from the best fit of the data. Thus, we seek a total HTC of the form:

$$h = h_{cd} + h_{cv} \cong \phi \cdot \frac{0.13 \cdot \rho D \cdot (Gr \cdot Sc)^{\frac{1}{3}}}{L} \cdot \frac{W_{s,\infty} - W_{s,w}}{1 - W_{s,w}} \frac{h_{fg}}{(T_\infty - T_w)} \tag{22}$$

Evaluating the mixture density as the arithmetic mean in the boundary layer, one has:

$$h = \phi \cdot 0.13 \cdot g^{1/3} D^{2/3} \left(\frac{\rho_w + \rho_\infty}{2}\right) \cdot \left(\frac{\rho_w - \rho_\infty}{\mu}\right)^{\frac{1}{3}} \cdot \frac{W_{s,\infty} - W_{s,w}}{1 - W_{s,w}} \frac{h_{fg}}{(T_\infty - T_w)} \tag{23}$$

The total HTC can therefore be computed if the factor ϕ, the diffusion coefficient D, the wall temperature and the wall species mass fractions are known. The latter are not a-priori known if there are more than one NC species. The procedure to compute the species wall mass fractions as well as the effective diffusion coefficient D is explained next.

4. SPECIES CONCENTRATIONS AND THE EFFECTIVE DIFFUSION COEFFICIENT

In binary mixtures such as steam-air, it is straightforward to compute the steam mass fraction at the wall, since the steam partial pressure is readily available if wall temperature and total pressure are specified. In the presence of more than one NC gas, e.g. air and helium, the procedure is more complex. Indeed, the helium diffusion coefficient in steam is substantially larger than that of air, typically by a factor of 4. As a result, helium will tend to have a mild concentration profile in the boundary layer, whereas air will have a sharper profile and accumulate more strongly at the liquid-gas interface. The effective diffusion coefficient is directly linked to the NC gas profiles, which in turn determine the molar concentration of the NC gases at the wall, and thus the condensation rate, as per equation (22). Using the Diffusion Layer Model, Peterson [17] has outlined a procedure to compute the effective diffusion coefficient when steam is in the presence of more than one NC gas. We follow this approach hereafter. Wilke [18] has derived the following expression for the effective diffusion coefficient D in multispecies environments:

$$D = \frac{X_{nc,ave}}{\sum_{j=1,2} \frac{X_{j,ave}}{D_{j,s}}} \tag{24}$$

In the above, $D_{j,s}$ is the binary diffusion coefficient of the jth NC species in steam, $X_{nc,\,avg}$ the average total NC mole fraction and $X_{j,\,avg}$ the average mole fraction of the jth NC species. The latter two parameters are defined as follows:

$$X_{nc,ave} \equiv \frac{X_{nc,\infty} - X_{nc,w}}{\ln(X_{nc,\infty} / X_{nc,w})} \tag{25}$$

$$X_{j,ave} \equiv \frac{X_{j,\infty} - X_{j,w}}{\ln(X_{j,\infty} / X_{j,w})} \tag{26}$$

The NC mole fractions at the wall are not a-priori known, and hence an iterative scheme is required to compute them. To start the iteration, one can assume that the wall mole fraction of the jth NC gas keeps the same proportion of the total NC as in the bulk, i.e.:

$$X_{j,w}^{o} \approx X_{j,\infty} \frac{X_{nc,w}}{X_{nc,\infty}} = X_{j,\infty} \frac{1 - X_{s,w}}{X_{nc,\infty}} \tag{27}$$

Since the steam mole fraction at the wall $X_{s,w}$ is known, one can use the above expression to compute an intermediate effective mixture diffusion coefficient at the nth iteration D^n from equation (24). Next, the following vector is computed:

$$X_{j,w}^{''} = \exp\left[\ln(X_{j,\infty}) - \frac{D^n}{D_{j,s}}\left(\frac{X_{nc,\infty} - X_{nc,w}^n}{X_{nc,ave}^n}\right)\right] \tag{28}$$

The updated j^{th} NC mole fraction at the wall is computed as follows:

$$X_{j,w}^{n+1} = X_{j,w}^{"} \frac{X_{nc,w}^{n}}{\sum\limits_{j=1,2} X_{j,w}^{n}} \tag{29}$$

Normally, a few iterations (order of 10) are required to achieve tight convergence. It was nonetheless found in the range of this investigation that a single iteration was already sufficient to yield reasonable accuracy. In general, it is found that the effective mixture diffusion coefficient is close to the diffusion coefficient of air in steam, and that the helium mole fraction at the wall is only slightly larger than its value in the bulk.

5. DATA COLLECTION AND REDUCTION PROCEDURE

5.1 The Data Sets

The raw data of the considered experiments were consolidated in a single data set for the purposes of generating a generalized correlation for steam-air-helium mixtures. The Dehbi et al. data [5] (steam, air and helium mass fractions, total pressure, wall temperature, wall subcooling, HTC) are read from the Appendix of the thesis by Dehbi [19]. The raw data from the cylindrical tube condenser are recovered by multiplying the HTC data by 1.25, a factor used by the authors to provide a conservative estimate for flat condenser surfaces.   The flat plate data by Anderson et al. [7] were directly obtained from the Appendix of the thesis by Anderson [120]. Since the author provides HTC measured by both the heat flux meter and the energy balance methods, an arithmetic mean was taken as representative of the data. The data by Liu et al. [8] (steam, air, helium mass mole fractions, wall subcooling, total pressure, HTC) were obtained from the Appendix of the Liu thesis [21]. The data by Su et al. [9,10] were obtained from the graphs presented in their papers (HTC, steam, air and helium mass fractions, wall temperature subcooling at isobaric conditions).

5.2 Correction for the Effects of Condenser Curvature

In natural convection flows over vertical surfaces, heat transfer rates are higher compared to those of flat plates, owing to radial curvature. Indeed, if the radius of curvature of cylindrical surfaces is of the order of the fluid boundary layer thickness, then curvature effects become noticeable. For practical reasons, most experimental investigators have used internally cooled cylinders as condensing surfaces. We follow hereafter the procedure outlined by Dehbi [11] to transform raw HTC data for curved surfaces into equivalent values for flat surfaces. Correction factors are different for different conditions (Gr number) and range from 1.09 to 1.20. In summary, the ranges of curvature correction factors applied to various data are shown in Table 2.

Table II. Curvature enhancement factors due to condenser curvature

Experiment	Range of Grashof numbers	Range of curvature correction factors
Dehbi (1991)	$5.0 \cdot 10^{9} - 1.5 \cdot 10^{11}$	1.11-1.14
Liu (2000)	$3.7 \cdot 10^{10} - 6.4 \cdot 10^{11}$	1.11-1.20
Su (2013, 2014)	$2.5 \cdot 10^{11} - 2.5 \cdot 10^{12}$	1.09-1.18

6. GENERALIZED CORRELATION OF THE HTC IN STEAM-AIR-HELIUM MIXTURES

The consolidated HTC data from the four experimental investigations were curve-fitted, assuming a single unknown fitting parameter ϕ which is solely a function of the Bird factor Θ. ϕ is assumed to include the enhancement due to suction, the small convective heat transfer contribution, the film resistance and any other effects (mist, etc.). The best fit of the data was obtained with the following expression for ϕ :

$$\phi = 1.17 \, \Theta = 1.17 \, \frac{\ln(1+B)}{B} \tag{30}$$

Simplifying, one gets an expression for the generalized HTC correlation:

$$h = 0.152 \, D^{2/3} \, (\rho_w + \rho_\infty) \left(\frac{\rho_w - \rho_\infty}{\mu} \right)^{1/3} \frac{h_{fg}}{(T_\infty - T_w)} \ln\left(\frac{1 - W_{s,w}}{1 - W_{s,\infty}} \right) \tag{31}$$

From Figure 2, one sees that the above correlation fits the consolidated data quite well over more than one order of magnitude in the values of the HTCs. Close to 90 % of the data are inside the $\pm$ 30% band, and the standard deviation is about 20 %, which is of the order of the typically quoted experimental errors. The relatively low scatter indicates that the raw data from the various sources are globally consistent with one another, and that there is no physical justification for the large deviations observed when one compares the HTCs based on the direct evaluation of the empirical correlations.
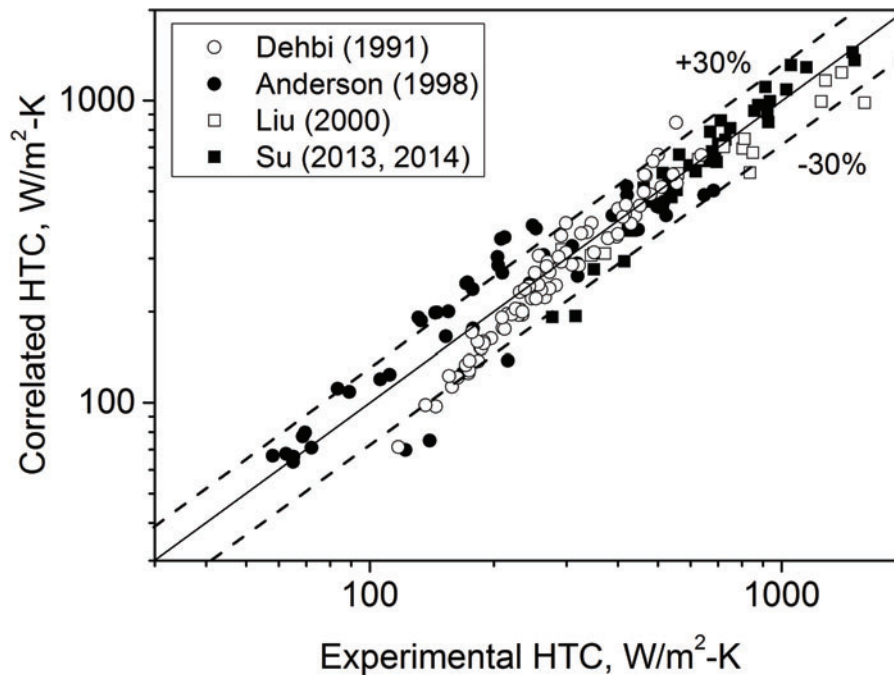

Figure 2: Correlation versus experimental data

7. PARAMETRIC STUDY ON HTC DEPENDENCIES

In this section, we clarify, based on the generalized correlation, the dependency of the HTC on the important physical parameters. For a given steam-air-helium mixture, the HTC, per equation (31), can be uniquely specified from four independent parameters, e.g. a) total pressure, steam fraction, helium (air) fraction, wall temperature; b) total pressure, steam fraction, helium (air) fraction, wall subcooling. If one fixes three parameters, the correlation will give a clear dependency of the HTC on the remaining variable parameter. This is the object of this parametric study section.

7.1. Effect of Pressure

We fix hereafter the steam mass fraction to 0.3 and 0.65, the helium mole fraction to 0.10 and 0.30, and the wall subcooling to 10 K, 30 K and 60 K, respectively. The variation of the HTC as a function of the imposed total pressure is shown in Figures 3. It is found that regardless of the steam mass fraction, the HTC varies roughly with pressure to the power 0.43, 0.50 and 0.56 for subcoolings of 10 K, 30 K and 70 K, respectively. The HTC is thus a strong function of pressure, and the strength of this dependency is higher the higher the degree of wall temperature subcooling. One also notes the large increase in the HTC as the steam content is increased, and the slight decrease in HTC as the helium mole fraction is increased from 0.10 to 0.30.
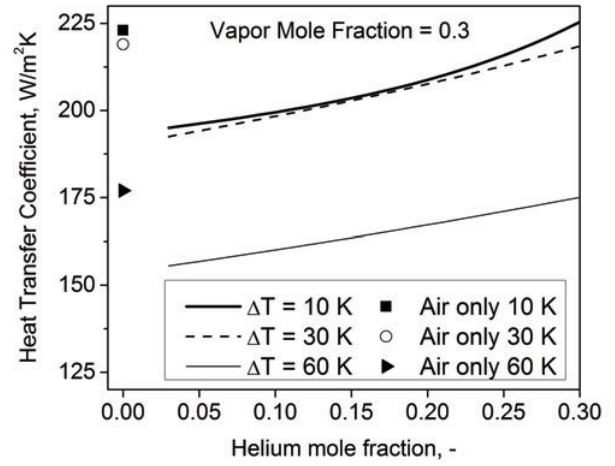
7.2. Effect of Helium Mole Fraction

We prescribe hereafter the steam mole fraction (0.3, 0.5, 0.7), the total absolute pressure (3 bars), the wall temperature subcooling (10 K, 30 K, 60 K), and vary the helium mole fraction. As displayed in Figures 4, the correlation predicts that the HTC increases as the helium fraction increases, i.e. as helium moles replace air moles in the NC mixture. This can be explained by the fact that due to its high diffusivity, the helium concentration (mole fraction) is roughly constant in the boundary layer. As more moles of helium replace air moles, the total NC mole fraction at the wall decreases, meaning more effective heat transfer. We also show HTC values for air-steam mixtures as evaluated from the generalized steam-air correlation given recently by Dehbi [11]. While the HTC is larger for air-steam than for air-helium-steam mixtures at low mole fractions of helium, the diffusive effect of the light gas causes the heat transfer to be more enhanced than with pure air at larger helium contents. It should be noted that the computations were made only for meaningful values of the helium mole fraction. Beyond a certain threshold of the latter, the total gas density at the wall becomes lighter than that of the bulk, and the helium separates from the rest of the mixture due to its larger buoyancy.

## 7.3. Effect of Wall Temperature Subcooling

We fix the steam mass fraction (0.3, 0.5, 0.7), the helium mole fraction (0.1, 0.3), the total absolute pressure (3 bars), and vary wall temperature subcooling up to 70 K. Results are shown in Figures 5. Up to small subcoolings of about 30 K, the HTC remains roughly unchanged. Beyond that, it decreases with subcooling to the power of roughly - 0.4. This dependency is approximately the same for steam-air mixtures as shown in [11].
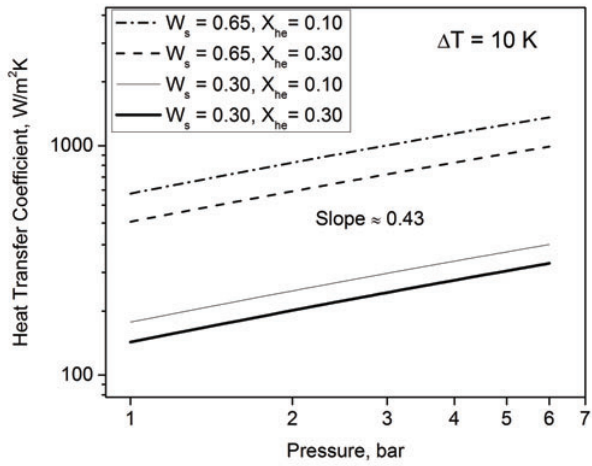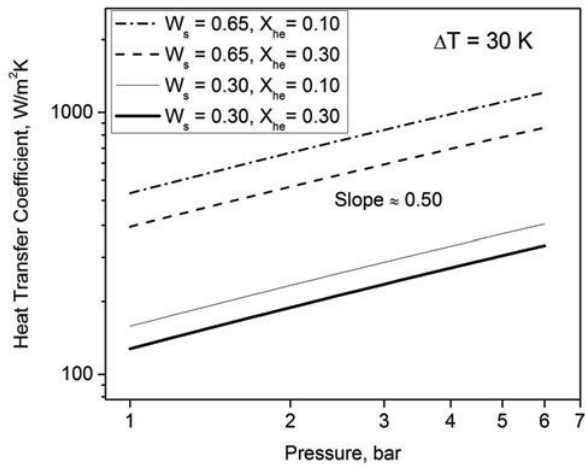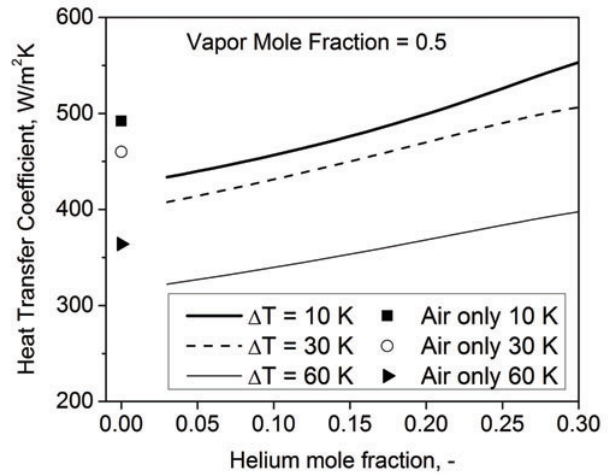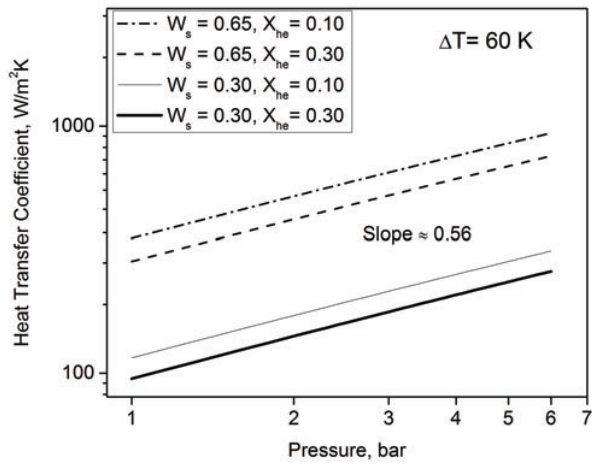
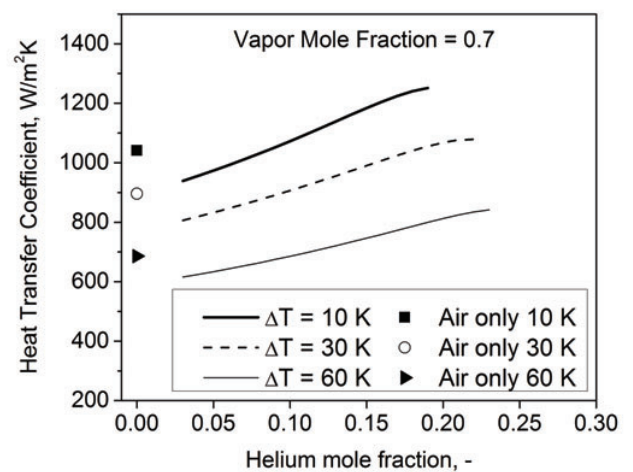Figure 3: Effect of pressure
  (a) ΔT= 10 K
  (b) ΔT= 30 K
  (c) ΔT= 60 K

Figure 4: Effect of helium mole fraction
  (a) Steam mole fraction = 0.3
  (b) Steam mole fraction = 0.5
  (c) Steam mole fraction = 0.7
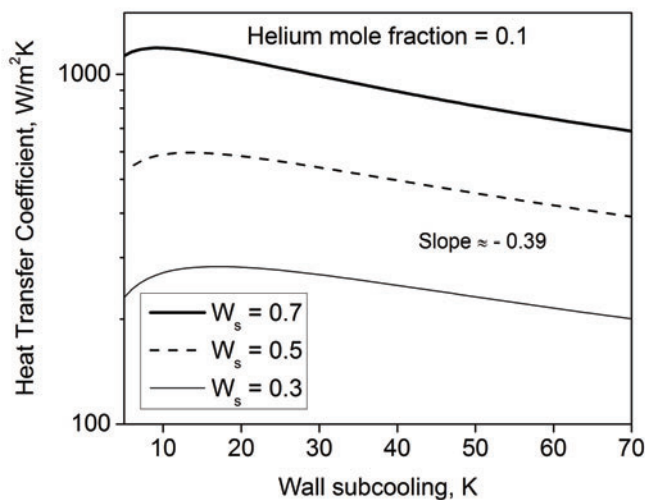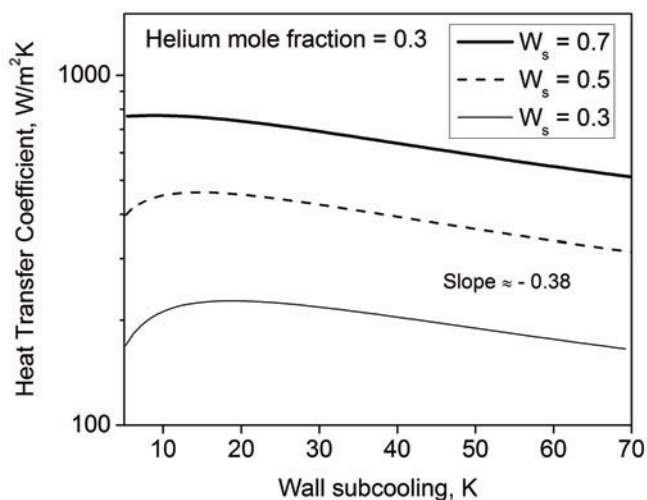
Figure 5: Effect of the wall subcooling.
(a) Helium mole fraction = 0.1
(b) helium mole fraction = 0.3

8. CONCLUSIONS

This investigation aimed at developing a generalized, best-estimate correlation for steam condensation in the presence of an air-helium mixture in turbulent free convection regimes for pressures up to 6 bars, helium mole fractions up to 0.4 and wall temperature subcooling levels up to 70 K. The correlation relies on data collected from four different experiments conducted over the past two decades, and is theoretically based upon the heat and mass transfer analogy. The HTC data collapse around a curve with a standard deviation of 20 %, within typical experimental error bands. The correlation provides clear dependencies of the HTC on the governing physical parameters such as the species mass fractions, pressure and wall temperature subcooling. Parametric studies using the generalized correlation show in particular the following results:

- All other things held constant, the HTC varies with pressure to a positive power in the range of 0.4 to 0.6. The higher the wall temperature subcooling, the greater this power. This result is independent of the species fractions.
- For a prescribed vapor mole fraction, the HTC increases as helium replaces equal air volumes in the mixture. At low helium moles fractions, the HTC is smaller than that of steam-air mixtures. Beyond a certain helium mole fraction threshold, the HTC is larger than that of steam-air due to the higher diffusivity of the mixture.
- All other things held constant, the HTC varies only slightly with wall temperature subcooling up to about 30 K. Beyond that, the HTC decreases with subcooling to a power of about - 0.4. This result is valid regardless of the species concentration.

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