Nuclear Engineering and Design 300 (2016) 601–609

Contents lists available at ScienceDirect

Nuclear Engineering and Design

journal homepage: www.elsevier.com/locate/nucengdes

A unified correlation for steam condensation rates in the presence of air–helium mixtures under naturally driven flows

A. Dehbi*

Paul Scherrer Institut, Villigen 5232, Switzerland

HIGHLIGHTS

- Correlation developed for condensation rates of steam in air–helium mixtures.
- Database consists of four consolidated works conducted in last two decades.
- Form of correlation deduced from heat and mass transfer analogy.
- Correlation gives clear dependency on critical thermal-hydraulic parameters.
- Correlation can be directly applied to steam–air–hydrogen mixtures.

ARTICLE INFO

Article history:
Received 11 August 2015
Received in revised form 26 January 2016
Accepted 4 February 2016
Available online 8 March 2016

K. Thermal hydraulics

ABSTRACT

Steam condensation in the presence of multiple 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. Experimentalists 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 binary 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 unified 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 in nuclear severe accidents. The consolidated raw data gather around a curve with a standard deviation of 20%, which is within typical experimental error bands. We show in addition that the correlation can directly be used to estimate steam condensation rates in the presence of binary hydrogen–air mixtures.

1. Introduction

Vapor film condensation in the presence of noncondensable gases (NC) is found in a wide range of applications, e.g. CO_2 separation (Ge et al., 2013), desalination plant condensers (Semiat and Galperin, 2001), variable conductance heat pipes (Dunn and Reay, 1994). In nuclear Light Water Reactors (Huhtiniemi and Corradini, 1993), steam condensation takes place on cold containment walls in the presence of air following a large pipe rupture accident. It is well established that the presence of even tiny amounts of NC gas produces a large reduction in steam condensation rates. In free convection regimes, this was highlighted by experiments of e.g. Al Diwani and Rose (1972) who found that the heat transfer rate was decreased by 50% with a NC gas mass fraction of just 1%. In forced convection, the reduction is also very significant, although not as dramatic. Wang and Tu (1989) for example have found that a 5% NC by mass causes a reduction of 50% in the heat transfer rate.

Theoretical explanations for the impeding effects of NC gases have been given by e.g. Minkowycz and Sparrow (1966) From the solution of boundary layer equations of vapor–NC mixtures, these authors showed that the NC gas accumulates near the gas-condensate film interface, greatly decreasing the local steam partial pressure, and consequently the condensation rate. A thorough review of condensation phenomena in the presence of a NC gas is given by the recent article of Huang et al. (2015).

Most of the works to date have involved the use of a single NC gas, e.g. air or nitrogen. In case of a nuclear plant severe accident with core melt, however, H_2 may also be present in the mixture.

---

* Tel.: +41 56 310 27 11; fax: +41 56 310 21 99.
E-mail address: abdel.dehbi@psi.ch

http://dx.doi.org/10.1016/j.nucengdes.2016.02.009
0029-5493/

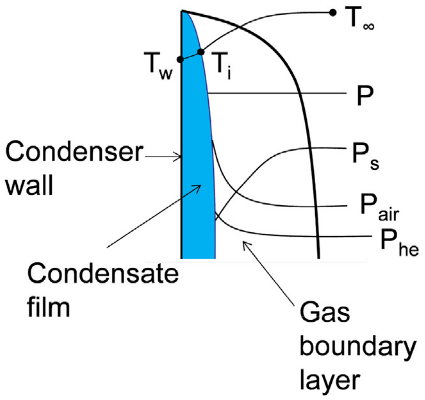

Fig. 1. Schematic of the diffusion boundary layer.

A handful of experimental investigators have addressed the presence of a light gas in addition to air, for example Dehbi et al. (1991), Anderson et al. (1998) Liu et al. (2000), and most recently Su et al. (2013, 2014), all of whom having used helium as a surrogate for H_2 for obvious safety concerns. The available correlations in these works have in common the fact that they are largely empirical fits of the particular data, which renders their general use rather problematic, in addition to sometimes quite different predictions of the HTC dependency on critical parameters. For example, Dehbi et al. (1991) correlated the HTC with the degree of wall subcooling to the power −0.25, while in the Su et al. (2014) correlation the HTC varies with the subcooling to the power −0.60. These apparent contradictory predictions are essentially due to the purely empirical way in which experimental data have been correlated.

When modeling steam condensation in air–hydrogen mixtures, analysts of nuclear plant hypothetical accidents often employ conservative correlations 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. This in turn leads to the underestimation of H_2 explosion risk, which is not acceptable.

To produce best-estimate simulations, it is important that vapor condensation correlations in the presence of air and hydrogen NC gases be based upon physical grounds rather than empiricism. In this work, we aim at proposing such a correlation that uses data collected by several authors in the past decades. We do away with the empirical correlations, and go back to the original raw data, consolidate them into a single set and propose a unified correlation. The form of this new correlation will be deduced from an analysis based on the heat and mass transfer analogy (HMTA).

2. Condensation rate from the heat and mass transfer analogy

2.1. The model

We hereby propose a model based on the HMTA to derive the form of the HTC as is traditionally done in the analysis of condensation in the presence of a single NC gas (Dehbi, 2015). We assume that the gas consists of an ideal mixture composed of two NC gases and water vapor, and that film condensation takes place under local thermodynamic equilibrium at the liquid–vapor interface.

When a steam–air–helium mixture flows over a cold condenser flat surface, a diffusion layer develops as shown in Fig. 1. If the condenser temperature is lower than the steam dew point temperature, the vapor 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. Thus the steam mole fraction at the gas–liquid interface is smaller compared to its 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 one moves closer to the gas–liquid interface, resulting in a deterioration in 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:

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

If radiation can be neglected, heat transfer consists of vapor condensation at the interface, sensible convection heat transfer from the bulk to the interface, and conduction through the liquid condensate. Under stationary conditions, one has:

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

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, while T_∞ refers to the steam saturation temperature in the bulk. The total HTC can then be written as:

$$h = \frac{1}{\left(1/(h_{\text{cd}} + h_{\text{cv}})\right) + 1/h_f} \tag{3}$$

If the total NC mass fraction is relatively large (greater than 0.1), the film resistance can be safely neglected, in which case T_i can be set to the wall temperature T_w. The total HTC reduces to:

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

The rate of diffusion of steam toward the condenser surface sets the condensation rate. At gas–liquid interface, the species mass fluxes of both steam and NC air–helium mixture interface include both convective and diffusive components. Based on the Bird et al. (2002) approach, the species mass fluxes can be written as:

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

$$\dot{m}''_s = \rho W_s v - \rho D \frac{\partial W_s}{\partial n} \tag{6}$$

v is the mixture velocity, D the effective mass diffusion coefficient, and n the normal direction to the wall (liquid film). *nc* and *s* denotes the total NC mixture and steam, respectively. Since the sum of the mixture mass fractions is 1, the mixture mass flux at the wall $\dot{m}''_w$ can be expressed as:

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

Furthermore, the NC impermeability condition at the interface can be expressed as:

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

As a result, the steam mass flux at the wall can be expressed as:

$$\dot{m}''_{s,w} = \frac{-\rho D\left(\partial W_{s,w}/\partial n\right)}{1 - W_{s,w}} \tag{9}$$

Alternatively, one can also formulate the condensation mass flux in terms of the mass transfer coefficient h_m:

$$\begin{aligned}\dot{m}''_{s,w} &= \frac{-\rho D\left(\partial W_{s,w}/\partial n\right)}{1 - W_{s,w}} = h_m \frac{W_{s,\infty} - W_{s,w}}{1 - W_{s,w}} \\ &= \frac{\rho D \cdot Sh_o}{L} \cdot \frac{W_{s,\infty} - W_{s,w}}{1 - W_{s,w}}\end{aligned} \tag{10}$$