THE DEAF METHODOLOGY FOR THE CORRELATION OF HEAT TRANSFER DATA OF WORKING FLUIDS AND MIXSTURES OF FLUIDS IN THE EVAPORATORS OF REFRIGERATING EQUIPMENT AND HEAT PUMPS

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Abstract. Owing to the phase-out of working fluids currently used in refrigerating equipment and heat pumps such as CFC and HCFC there is need for searching new fluids, whose thermodynamic and transport properties aren't available and there are few heat transfer data for the evaporators and the condensers. The present methodology is founded on a new approach which utilizes a suitable hydrodynamic model for Poli–Phase Flow derived by the original and powerful "Drift Flux Model" of G. B. Wallis and it has been successfully applied by the Authors to correlation of heat transfer data for the heat transfer equipment of the refrigeration plants and heat pumps to predict the heat transfer during evaporation and condensation of working fluids and mixtures of fluids. A wide data bank of heat transfer data derived from various papers of the literature have been correlated with a very high correlation coefficient (0,85 ÷ 0,95) both for pure fluids and fluid mixtures. The present paper explains the methodology and gives some results of typical application.

INTRODUCTION

The phase-out of working fluids currently used in refrigerating equipment and heat pumps such as CFC and HCFC gives rise to a lot of problems. There is need for searching new fluids, whose thermodynamic and transport properties aren't available and there are few heat transfer data for the evaporators and the condensers.

The Authors since some years developed a new correlation methodology of heat transfer data in this kind of equipment. The methodology is based on a new approach which utilizes a suitable hydrodynamic model for Poli–Phase Flow. This last is derived by the original and powerful model of the Drift Flux of G. B. Wallis which is, essentially, a separated-flow model in which attention is focused on the relative motion rather than on the motion of the individual phases. The model of Wallis has been widely applied to the hydrodynamic study of two-phase flow but no application is reported in the technical literature on heat transfer.

The new methodology has been successfully applied by the Authors to correlation of heat transfer data in Fluidized Beds (Dispenza et a. 1992, 1997) up to very high temperatures when there is need to consider the effect of the thermal radiation. In the field of heat transfer equipment for the refrigeration plants and heat pumps, the methodology has been, applied to predict the heat transfer during evaporation (Columba et a. 1996, 1999, 2001; Dispenza A., Panno D. 2001) and condensation (Columba et a. 2001) of the working fluids and mixtures of fluids. A wide data bank of heat transfer data derived from various papers of the literature have been correlated with a very high correlation coefficient (0,85 ÷ 0,95). Pure fluids analyzed

comprehend: water, some hydrocarbons, a lot of refrigerants both new and conventional, NH_3, CO_2 and some working mixtures of fluids.
The application of the model to the evaporation and condensation of pure working fluids and working mixtures of fluids accounts for the entrainment of liquid in the gas core in two-phase annular flow and considers the effect of interfacial phenomena. This is a new kind of approach in heat transfer which, by means of a basic suitable drift-flux one-dimensional model, allows to afford, at least, the main relevant aspects of the problems arising in heat transfer. The stirring action due to the evaporation and the buoyancy for the whole section of a duct or in the liquid film in annular flow is accounted considering some bi-dimensional effects.
The poster and the related paper explains the methodology, gives some results of typical applications and reports some information about the whole research activity in course at DEAF in relation to the subject of the Conference.

THE "DRIFT FLUX MODEL" OF G.B. WALLIS

Both diabatic and adiabatic Two-Phase Flow Models are based on One-Dimensional Hydrodynamic Models, these consider the phenomena occurring during the flow on a stationary basis (Hestroni, 1982; Hewitt, Hall-Taylor, 1970; Wallis, 1969).
The models currently used are the following:
- the homogeneous model, which considers the flow of a homogeneous mixture
- the separated model, which considers the flow of a stream of vapor in the central core of a duct and an annular stream of liquid flowing in the region near to the wall
- the separated model with entrainment of liquid, which considers the flow of a stream of vapor in the central core of a duct, an annular stream of liquid flowing in the region near to the wall and an ideal stream of liquid droplets entrained in the central core of the duct.

In each model the streams in a duct cross section are considered in thermodynamic equilibrium and the static pressure is the same for each stream; the approach is Eulerian.
One relevant parameter in the separated models is the Slip Ratio for a cross section lying along the flow path, this parameter is defined as the ratio between the mean vapor velocity and the mean liquid velocity. In the homogeneous model the value for the Slip Ratio is 1.00. In the separated model with entrainment of liquid droplets the Slip Ratio is defined in the same mode but it is considered, for the liquid phase, only the stream flowing in the annular region near the wall.
The equations needed to study the flow process are reported in the following paragraph for the Model proposed by the Authors which is comprehensive of both the separated and the separated model with entrainment.
The Drift Flux of G. B. Wallis (Wallis, 1969) is based on a different approach and it considers, essentially, a separated-flow model in which attention is focused on the relative motion rather than on the motion of the individual phases. The model of Wallis has been widely applied to the hydrodynamic study of two-phase flow but no application is reported in the technical literature on heat transfer.
Dealing with the flow process, which is considered stationary and one-dimensional, the flow is that of an ideal two-phase mixture which travels along the duct with a mean velocity j.
Looking at a cross section along the flow path, travelling at a velocity j, and bearing in mind a reference frame travelling at the same velocity (see figure 1), the flux can be decomposed in two fluxes:
- a flux with a velocity j (which is time independent for the stationary hypothesis on the flow)
- another flux with some drift velocities for each phase, in respect to the mobile reference

frame.

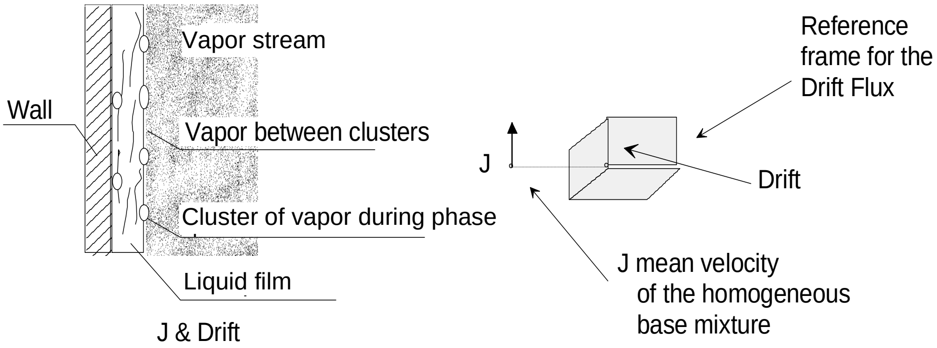

Figure 1 – The Hydrodynamic model

The model (see Wallis, 1969) gives a lot of advantages for the appropriate study of two-phase one-dimensional flow.

THE DEAF "DRIFT FLUX MODEL" FOR THE CORRELATION OF HEAT TRANSFER DATA DURING THE EVAPORATION OF PURE FLUIDS AND MIXTURES OF FLUIDS

The DEAF "Drift Flux Model", for the process of heat transfer data during the evaporation and condensation of pure fluids and mixtures of fluids, is a very powerful tool for derivation of correlations to predict the heat transfer coefficient suitable for design and testing of the equipment performance. Moreover, the model has been successfully applied to correlation of heat transfer data in fluidized bed heat exchangers and in fluidized bed heat combustors.
As an example, let it be considered as the model works for the correlation of heat transfer data during the evaporation of pure fluids and mixtures of fluids.
The hydrodynamic model is based on the following hypotheses:

- in the entrance region of the duct, when boiling begins, some vapor bubbles born out near the heated wall, due to the "Bernoulli effect" bubbles come out towards the central core; this kind of behavior persists along the duct up to the region where there is the Churn/Plug flow, then, downstream, there is the Annular flow region
- in the region of the Annular flow there is an annular stream of liquid flowing in the duct, and, from the wall to the interface the temperature varies from T_p (near the wall) to T_s (saturation temperature, at the interface); in the liquid film, near some nucleation sites, born out vapor bubbles, which come towards the interface where they splash in the vapor core stimulating droplet entrainment and at the interface there is, also, some convective vaporization
- in the central core travels a vapor stream, at a mean temperature T_v, entraining droplets of liquid.

The Hydrodynamic model

The equations of the model proposed by DEAF belong fully with the region of the annular flow, the subscript *lf* indicates parameters for the liquid film, the subscript *v* indicates parameters for the vapor core, the subscript *lg* indicates parameters for the stream of liquid droplets entrained in the central core:

A cross section area of the duct (e.g.: pipe of diameter D);
W liquid flow rate flowing at the duct inlet;

For a cross section of the duct:
α volumetric fraction of vapor;
β volumetric fraction of liquid flowing in the film;
x mass fraction of vapor;
E mass fraction of liquid entrained as droplets in the vapor core;
$G = \frac{W}{A}$ mass velocity of the mixture;
$j_v = \frac{G\,x}{\rho_v}$ superficial vapor velocity;
$j_{lf} = \frac{G(1-x)(1-E)}{\rho_l}$ superficial vapor velocity of liquid film;
$j_{lg} = \frac{G(1-x)E}{\rho_l}$ superficial vapor velocity of entrained phase;

absolute velocities of the phases (referred to a Reference frame which is fixed to the wall of the duct) can be given by the following equations:

$$u_v = \frac{j_v}{\alpha}, \qquad u_{lf} = \frac{j_{lf}}{\beta}, \qquad u_{lg} = \frac{j_{lg}}{1-\alpha-\beta}$$

usually it can infer $u_{lg} \approx u_v$, This is a suitable hypothesis for problems encountered in engineering practice (Hewitt, Hall-Taylor, 1970), so:

$$\beta = 1-\alpha-\frac{\alpha\,E\,(1-x)}{x\rho^*}, \qquad \text{where } \rho^* = \frac{\rho_l}{\rho_v}$$

the Slip Ratio for the proposed model can be defined as:

$$k = \frac{u_v}{u_{lf}}$$

mean velocity j for the base homogeneous two-phase mixture (j is the velocity of the "Drift Flux" mobile reference frame), in the Model of Wallis, is given by:

$$j = j_v + j_{lf} + j_{lg}$$

this implies that:

$$j = \frac{W}{A\rho_m} = G\left[\frac{x}{\rho_v} + \frac{(1-x)(1-E)}{\rho_l} + \frac{(1-x)E}{\rho_l}\right]$$

so:

$$v = \frac{1}{\rho_m} = \frac{x}{\rho_v} + \frac{(1-x)(1-E)}{\rho_l} + \frac{(1-x)E}{\rho_l}$$

if E=0 it is obtained as a particular case the usual formula for the specific volume of the saturated vapors[1].

In the present Model the mean velocity is defined as: $j = \frac{G}{\rho_f}$

[1] note that the density ρm=1/v is different from the "Photographic density" used in this model

in which ρ_f is the "Photographic density": $\rho_f = \rho_v x + \rho_l (1-x)$

The Drift velocity v_v^* *of the vapor* is given by the equation:

$$v_v^* = \frac{j_{vj}}{\alpha} = u_v - j$$

where j_{vj} is the Drift flux of the vapor: $j_{vj} = \alpha (u_v - j)$.

The Drift velocity v_{fj}^* *of the liquid film* is given by the equation:

$$v_{fj}^* = \frac{j_{fj}}{\beta} = |u_{lf} - j|$$

where j_{fj} is the Drift flux of the liquid flowing in the film:

$$j_{fj} = \beta (u_{lf} - j)$$

The Slip Ratio k is given by the formula of Levy–Zivi, derived applying the criterion of the "Minimum Entropy Production" of Glansdorff and Prigogine to two-phase flow:

$$k = \left(\frac{\rho^* + E \frac{1-x}{x}}{1 + E \frac{1-x}{x}} \right)^{1/3}$$

α is given by the equation derived by Zivi:

$$\alpha = \left[1 + \frac{E}{\rho^*}\left(\frac{1-x}{x}\right) + (1-E)\rho^{*^{-2/3}}\left(\frac{1-x}{x}\right)\left(\frac{1 + \frac{E}{\rho^*}\left(\frac{1-x}{x}\right)}{1 + E\left(\frac{1-x}{x}\right)} \right)^{1/3} \right]^{-1}$$

The mass fraction E entrained as droplets in the vapor core can be estimated with a methodology proposed by Dispenza (Dispenza 1980, 1987). The account for the entrainment in two-phase diabatic flow allows application of the present methodology to a lot of technical problems.

The methodology for estimation of E is based on the application of a correlation derived by Dispenza for the case of hydrodynamic equilibrium between entrainment and deposition when $E = E^*$:

$$E^* = \frac{C_1}{x^3\left(e^{\frac{C_2}{x}} - 1\right)}$$

here:

$$C_1(\pi) = 2{,}0382 - \frac{0{,}6787}{\pi^{0{,}25}} \quad C_2(\pi) = 1{,}4647 + \frac{2{,}044 \cdot 10^{-3}}{\pi^2} \quad \pi = \frac{\mu_v^{0{,}25}}{\sigma \rho_v}\rho^*$$

σ is the surface tension.

The entrainment has relevance during the evolution of diabatic two-phase flow in a boiling duct. Main causes which give rise to entrainment of liquid droplets into the vapor core are:

- droplets creation due to heterogeneous nucleation
- mechanism of droplets entrainment resulting from emission of bubbles from waves on the liquid film surface
- mechanism of droplets creation due to the vaporization

it is worth of note that during vaporization there is a competition between the entrainment and the deposition of droplets.

The main parameters in the Drift Flux model with entrainment of DEAF are x, E, α, β.

E^*, considering hydrodynamic equilibrium, is estimated with the above correlation (Dispenza 1980), then it is estimated E which accounts for the heat transfer along the flow path (Dispenza 1980, 1987):

$$E = \frac{E_1(1-x_1)}{1-x} e^{-\frac{k^*}{\sqrt{\rho^*}}(z-z_1)} + \frac{k^*}{\sqrt{\rho^*}} \frac{e^{-\frac{k^*}{\sqrt{\rho^*}}z}}{1-x} \int_{z_1}^{z} \left[E^*(1-x) e^{\frac{k^*}{\sqrt{\rho^*}}z} \right] dz$$

the needed parameters are: vapor mass fraction at duct inlet x_1, mass fraction of liquid entrained as droplets at the duct inlet E_1, the geometrical coordinate of the inlet cross section z_1, moreover, there is need to have the value of k* (mass transfer coefficient): this parameter can be estimated with a method proposed by Hewitt.

A typical trend of E versus x is reported in figure 2.

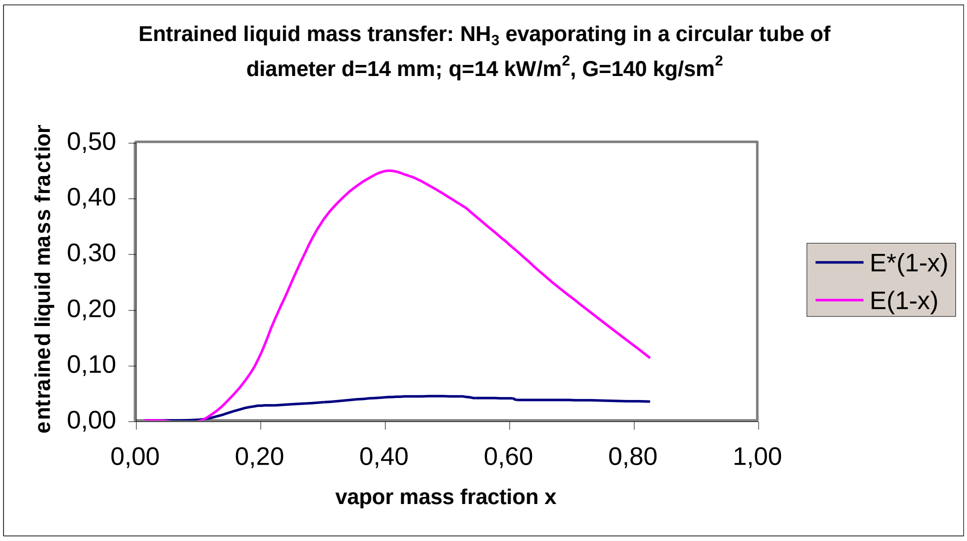

Figure 2 – Drift Flux Model – DEAF: Trend of E and E in an evaporating system*

Correlation of heat transfer data

The prediction of the Heat transfer coefficient during vaporization in tubes (Flow boiling) is of relevance in the field of Engineering (e.g.: Steam generators, Evaporators of refrigerating equipment and heat pumps, Chemical engineering, etc.).

The leading idea of the DEAF methodology is the use of a suitable hydrodynamic model for the estimation of the contribution due to the most relevant phenomena which originate along the flow path. The results obtained are reliable both for prediction of the mean and local heat transfer coefficient during evaporation of pure fluids and mixtures of fluids flowing in a duct (Dispenza A., Panno D. 2001, Columba et a. 2001).

Accounting for some contributions to heat flux which are considered in parallel:

$$q = q_c + q_v + q_{nb} + q_{mc} = h\,(T_p - T_m)$$

the heat transmission coefficient can be decomposed in four parts:

$$h = h_c + h_v + h_{nb} + h_{mc}$$

a) h_c can be estimated with the use of correlations reported in technical books, it account for the macro-convection attributable to the flow in the duct of a homogenous two-phase mixture travelling at a mean velocity j
b) h_v accounts for heat exchange at the interface between the liquid film and the vapor core, in this term there is no account for convective vaporization
c) h_{nb} accounts for the contribution due to the bubble creation at the heating wall
d) h_{mc} is the contribution for the convective vaporization and it can be estimated using a general correlation derived at DEAF: this contribution accounts for the micro-convection due to the stirring action of the vapor bubbles during their migration and their drift.

Let consider the heat transfer for a horizontal boiling duct heated at constant heat flux along all the flow path.

The contribution h_c

This contribution accounts for the boundary conditions on convective phenomena which occurs in the pipe, though, from the data analyzed, their influence results comparatively small.

It is considered a flow of an ideal two-phase mixture having the following characteristic dimensionless parameters:

$$Re = \frac{j\ X\ \rho_f}{\mu_m}; \qquad Pr = \frac{c_p \mu_m}{k_m}; \qquad Nu = \frac{h_c\ X}{k_m}$$

the properties of two-phase mixture are estimated with the equations:

$$\rho_f = \alpha\rho_v + (1-\alpha)\rho_l, \qquad \mu_m = x\nu_v + (1-x)\mu_l$$

$$k_m = \frac{k_l\ k_v}{k_v(1-\alpha) + k_l\ \alpha}, \qquad c_{pm} = c_{p_v} x + c_{p_l}\ (1-x), \qquad j = \frac{G}{\rho_f}$$

To estimate h_c for the case of vaporization in a circular pipe, can be used the Colburn correlation, which is suitable for turbulent flow:

$$Nu = 0{,}023\ Re^{0,8}\ Pr^{0,33}$$

$X = D_i$, internal diameter of pipe.

The contribution h_v

This contribution accounts for the interfacial heat transfer between the liquid film and the vapor core in the region of annular flow, when estimating this term there is no account for the convective contribution.

Bearing in mind that v_v* is the drift velocity for the vapor phase in the core and that the characteristic diameter is $D\text{-}2\delta$, the Reynolds Number Re_v is defined:

$$Re_v = \frac{v_v^*(D-2\delta)\rho_v}{\mu_v}$$

considering the value of this parameter, can be used a suitable correlation for one-phase flow in pipes such as the well known Colburn correlation for turbulent flow:

$$Nu = 0{,}023\ Re^{0,8}\ Pr^{0,33}$$

$$Nu = \frac{h_v^{*'}(D-2\delta)}{k_v}$$

The coefficient $h_v^{*'}$ is that suitable for the “effective surface” interested to the heat transfer:

$$h_v^{*} = h_{v^{*'}} \frac{T_{sat}-T_v}{T_p-T_{sat}} \frac{D-2\delta}{D}$$

$T_{sat} – T_v$ is estimated using the energy equation applied to the flow of the vapor in the Reference frame for the Drift flux, accounting for the velocity term.

The contribution h_{nb}

The effect of the mechanism of nucleate boiling can be estimated with the aid of correlation such as that of Rohsenow, of Forster and Zuber, of Mikic and Rohsenow, of various Russian Authors: Kutateladze, Tolubinskii, Kroujiline, Borishanskii which accounts for the effect of pressure for a lot of fluids using the Theory of Thermodynamic Similarity, of Stephan and Abdelsalam.

In the Data analysis made by the DEAF has been used the correlation of Cooper (Cooper 1984) which allows the derivation of the heat transfer coefficient due to nucleate boiling h_{nb} at a given pressure when it is considered a system at controlled heat flux and are known: q, the fluid and its properties, the surface roughness of the heating wall:

$$\sqrt[3]{q} = 55(T_p - T_s)\, p_r^{\,0{,}12-0{,}2\log(\frac{R_p}{R_{pr}})} (-\log p_r)^{-0{,}55} M^{-0{,}5}$$

in this formula:

$p_r = p/p_c$ is the reduced pressure of the two-phase system

R_p is the surface roughness in μm ($R_p = \mathbf{O}(0{,}1 \div 10\ \mu m]$)

$R_{pr} = 1$ μm is a reference roughness for the wall (1 μm)

M is the molecular mass of the fluid in kg/mole

here are known: q, p_r, R_p, M, so is estimated $T_p – T_{sat}$:

$$h_{nb} = \frac{q}{T_p - T_{sat}}$$

from the data analyzed results that the methodology is very effective.

It is worth of note that there is need to account for the contribution of the convective vaporization which takes place downstream to the region of flooding in bubble flow. This happens when the bubbles fill all the entire region of the pipe, then in a region downstream there is the region of Churn/Plug and Slug flow and downstream, the region of Annular flow.

When there is stratified flow, both with or without waves, in some region of the pipe a stream of liquid flows in a channel on the wall and there is an intensive surface nucleation at the interface, then the convective vaporization can be not relevant and the difference:

$$h - h_c - h_v = h_{nb} + h_{mc}$$

is represented only by the term h_{nb} (Dispenza A., Panno D. 2001).

The contribution h_{mc}

This contribution accounts for the convective vaporization; it is derived analyzing the experimental data and taking the difference:

$$h_{mc} = h - h_c - h_v - h_{nb.}$$

The structure of the correlation has been derived with the methods of Dimensional Analysis, studying, also, some analogies. The result obtained can be reported as an equation belonging with the Colburn Analogy, it is obtained:

$$J_{mc} = \frac{Bi_{mc}}{Re_b \ Nv^n}.$$

In the above equation Bi_{mc} is the Biot Number for the continuous phase defined using h_{mc}: it accounts for the role played by vaporization clusters during heat transfer from the liquid film due to the convective vaporization, taking into account the conjugate condition at the film interface:

$$Bi_{mc} = \frac{h_{mc} D_b}{k_l}$$

Re_b is a Reynolds Number defined by means of a suitable liquid[2] drift velocity due both to the flow and to the stirring action of the bubbles:

$$Re_b = \frac{v_b^{**} \ D_b \ \rho_l}{\mu_l}.$$

D_b is the mean diameter of vapor bubbles at the detachment from the heating wall and it can be estimated with the Fritz formula:

$$D_b = C\beta \sqrt{\frac{2\sigma}{g(\rho_l - \rho_v)}}$$

Nv can be interpreted as a dimensionless number which is characteristic for the particular problem (e.g.: in mass transfer there is need for the Schmidt Number which plays a seeming role, the same happens in one-phase convection for the Prandtl Number):

$$Nv = \frac{k_{eq}/2}{k_l} = \frac{h(\delta/2)}{k_l} = \frac{q}{\Delta T}\frac{\delta/2}{k_l}$$

$k_{eq}=h\delta$	is a mean equivalent conductivity of the liquid film in the region where there is bubbly flow
$\Delta T=T_p-T_m$	is the wall superheat in the region when is estimated k_{eq}
k_l	is the thermal conductivity of the liquid phase.

CORRELATION OF HEAT TRANSFER DATA DURING THE EVAPORATION OF PURE FLUIDS

Some experimental data allowed the derivation of a generalized correlation of heat transfer data when there is Annular flow. In this case the convective vaporization plays a relevant role.
In the figure 3 is reported the correlation derived at DEAF processing some data of LENI, Losanna, Switzerland and some data of the Technical University of Hannover, Germany (A. Dispenza e D. Panno 2001), all the data belong with experiments made working with ammonia in horizontal ducts.
LENI's data are derived working at a saturation temperature of 4°C, Hannover's data are derived working at a saturation temperature of –20°C.
The exponent of *Nv* obtained is zero; indeed by the analysis of optimization performed on this exponent taking into account the correlation coefficient results that when n=0 R^2 takes a

[2] v_b** accounts for the drift of the liquid phase in the liquid film and the drift of bubbles due both to the stirring effect caused by boiling phenomena and the local effect of buoyancy

maximum value.
Although the sample analyzed indicates that the parameter *Nv* shouldn't needed, bearing in mind that the data analyzed belong only to a same fluid, other work is needed.

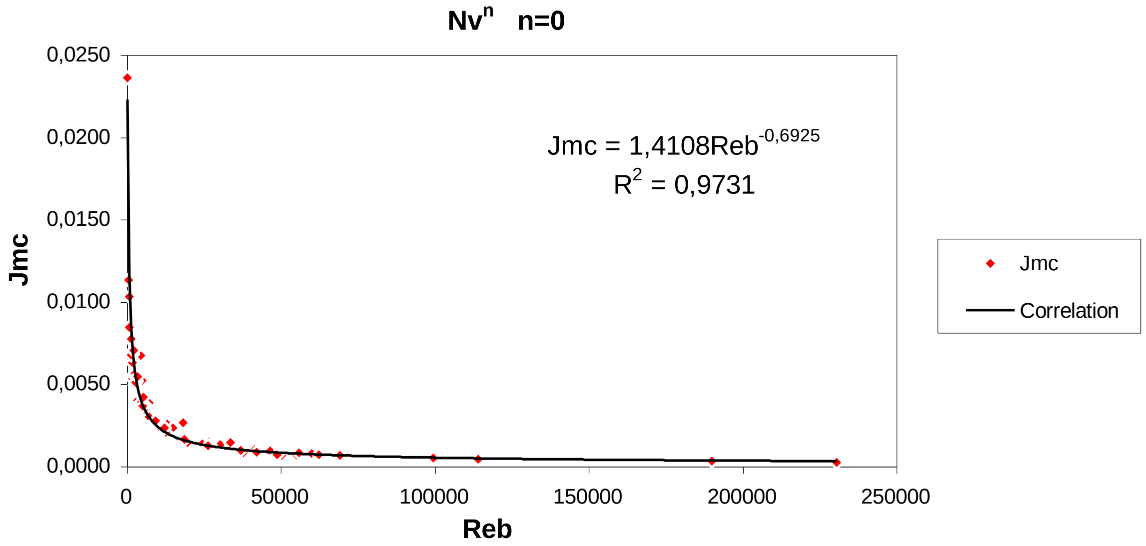

Figure 3 – Correlation derived at DEAF from LENI's data and University of Hannover data: ammonia boiling in a horizontal pipe.

In figure 4 it is reported a comparison between the values of h obtained by means of the correlation and those derived experimentally: the errors lie in the range +/- 20%.

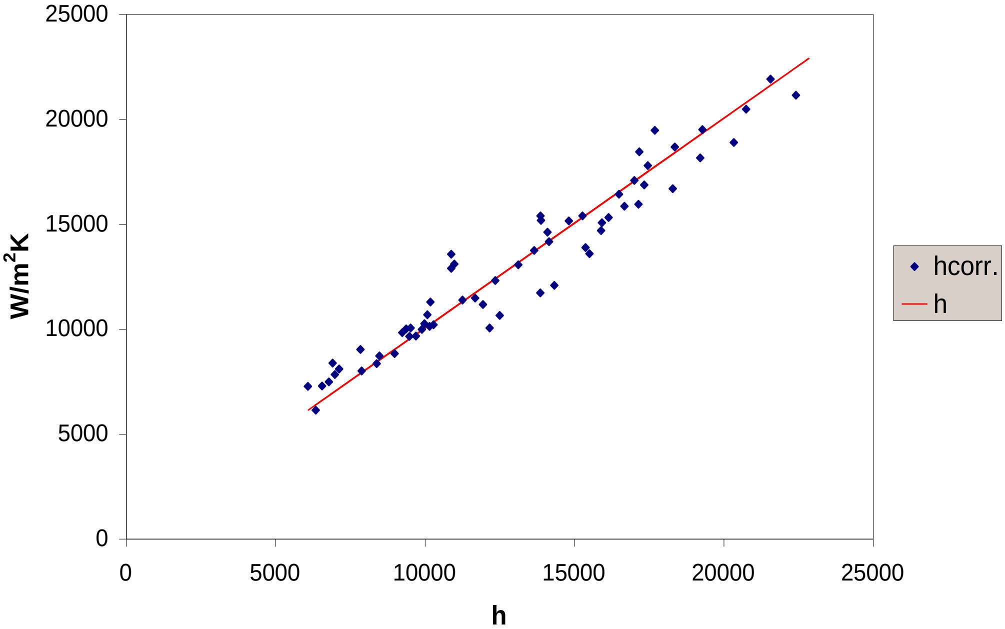

Figure 4 – Comparison between the values derived from experimental data and the correlation.

CORRELATION OF HEAT TRANSFER DATA DURING THE EVAPORATION OF MIXTURES OF FLUIDS

The DEAF Methodology has been applied for processing data of boiling mixtures of fluids. Data analyzed are results of experiences made at Department of Mechanical Engineering, University of Maryland, College Park, U.S.A. (Columba et a. 2001).
The heat transfer coefficient is decomposed in four contributions:

$$h = h_c + h_v + h_{nb} + h_{mc}$$

as in the case of pure fluids.
The result of the dimensional analysis made to derive the structure of the correlation leads to define a Colburn Number J_{mc} :

$$J_{mc} = \frac{Bi_{mc}}{Re_b\ Nv^n}\frac{1}{\xi^u}\ .$$

Nv is defined as for the pure fluids, the exponent n is derived interpolating experimental data, another factor is introduced which accounts for the composition of the mixture (for the case examined it is a binary mixture) and it can be the molar fraction ξ.
Correlating experimental data for mixtures by means of the three dimensionless Numbers: J_{mc} , Re_b, N_v it is obtained:

$$J_{mc} = a\ (Re_b)^m.$$

The estimation of thermodynamic and transport properties for the mixtures of fluids requires appropriated methodologies which can be applied working with an electronic sheet employing a program such, as Microsoft-Excel® (Columba et a. 2001). For data analyzed it is obtained that n=0 and u=4. Although the sample analyzed includes few data, the correlation coefficient is high R^2=0,91 (R=0,95): see figure 5.

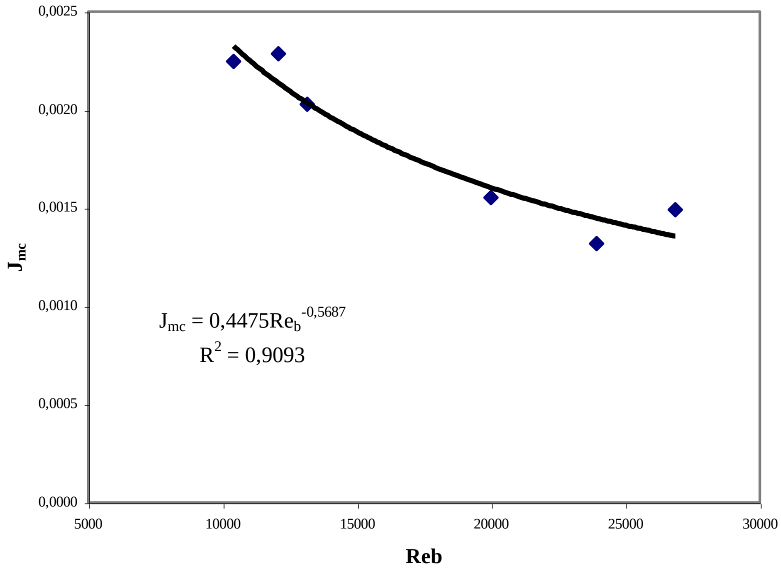

Figure5 – Correlation of experimental date for binary mixtures of fluids

Other work is in course at DEAF on these topics.

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