1986

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Stolk, A. L. and Waszenaar, R. H., "Heat and Mass Transfer Phenomena in an Absorber with Drop-Wise Falling Film on Horizontal Tubes" (1986). *International Refrigeration and Air Conditioning Conference.* Paper 31.
http://docs.lib.purdue.edu/iracc/31

HEAT AND MASS TRANSFER PHENOMENA IN AN ABSORBER WITH DROP WISE FALLING FILM ON HORIZONTAL TUBES

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1. ABSORBER DESIGNS

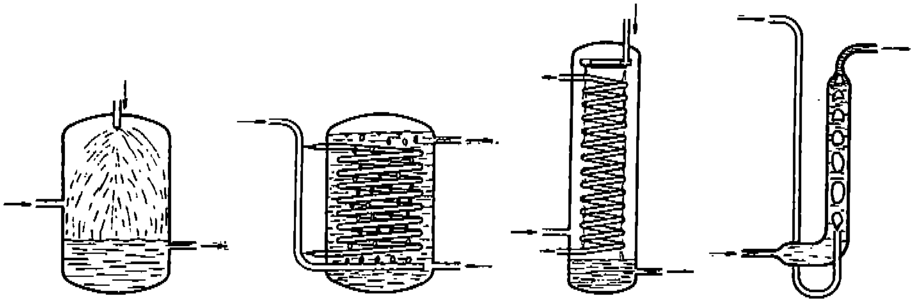
In thermal absorption cycles, as used for refrigeration machines, heat pumps and heat transformers, the absorber is a crucial component in optimizing the C.O.P. of the system. The combination of heat and mass transfer leads to complicated phenomena occurring in these absorbers.

The search for optimally working apparatus resulted into a number of designs. In the design three important points have to be considered:

a. The interface surface between vapour and absorbent has to be as large as possible.
b. The boundary layer of the absorbent has to be refreshed continuously.
c. The absorption heat is to be withdrawn at nearly the same place as it is developed.

To meet the first demand one of the phases has to be dispersed into the other one. The first choice to be made is whether the vapour or the liquid will form the continuous phase. Solid absorbers are not regarded in this paper.

If the liquid is in the continuous phase the vapour is dispersed into bubbles, feeded at the bottom of a bubble column or a vertical tube. In the other case the liquid is sprayed into the vapour or forms a falling film in a packed column, on vertical tubes or on horizontal tubes. Also a helical tube is being applicated. Some types of absorbers are given schematically in figure 1.



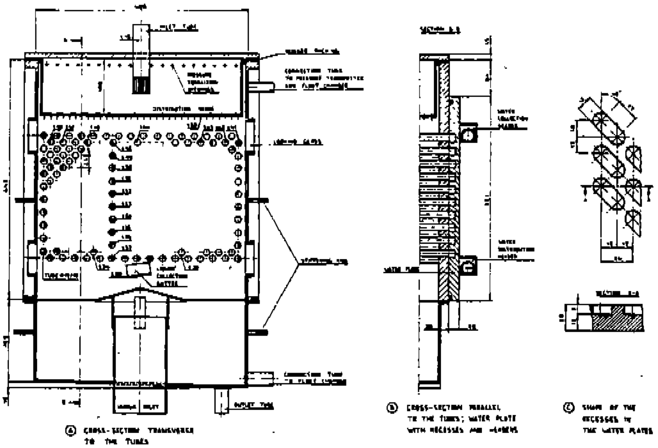
Spray absorber   Bubble absorber   Filmabsorber   Tube bubble absorber

Fig. 1 - Different types of absorber design for thermal sorption systems.

The spray absorber has the disadvantage that the drops cannot release the absorption heat during their travel through the vapour space. So, the third design demand is not fulfilled. The falling film absorber is much better in this respect if the film is formed over cooled tubes, because the absorption heat is being withdrawn directly through the thin liquid film. Due to the fact that relative low mass flows mostly are involved the film will often be laminar or, at a maximum show a wavy flow. The helical cooling tube will give a certain amount of mixing of the boundary layer with the bulk of the liquid film. However, an interesting study of Uddholm /1/ shows that under certain circumstances the film on a smooth vertical tube can become wavy, which gives a much better mass transfer than on smooth laminar films.

Another problem with falling film absorbers is that complete wetting of the heat and mass exchanger surface is very difficult. This is happening especially in viscous liquids. The vertical tube bubble absorber, as described by Keizer /2/ and Infante Ferreira /3/, has the advantage that along the slugs a complete and stable liquid film is formed inside the tube, but the fact that the liquid-gas column causes an extra pressure loss makes this type not suitable for low pressure working fluids.

Iedema /4/ proposed a drop wise falling film on horizontal tubes for absorbers. Experiments showed that a rather good wetting can be obtained when the design is optimal and that a good amount of mixing occurs, enhancing heat and mass transfer and retaining the advantage of a low pressure drop. This design is very suitable for low pressure media and viscous absorbents.


Ⓐ CROSS-SECTION TRANSVERSE TO THE TUBES

Ⓑ CROSS-SECTION PARALLEL TO THE TUBES; WATER PLATE WITH RECESSES AND HEADERS

Ⓒ SHAPE OF THE RECESSES IN THE WATER PLATES

Fig. 2. - Horizontal tube absorber for drop wise falling film.

Wassenaar and Van der Lans did fundamental research on this topic by means of models and experiments. A schematic drawing of this type of absorber is given in figure 2.

2. EXPERIMENTAL CONDITIONS

In the absorber a mixture of $LiBr/ZnBr_2/CH_3OH$, at mole fraction $LiBr:ZnBr_2 = 2:1$, flows around the tubes, absorbing CH_3OH vapour and releasing the heat of absorption to the cooling water, flowing inside the tubes. The mentioned mixture is rather viscous in the region of the mass-fraction; methanol $w = 0,29 - 0,35$ kg/kg and the temperature range is $\theta = 30 - 60^{o}C$. The viscosity range in this case is $\eta = 38,9 - 10,1$ cP, compared with water: 0,8 - 0,5 cP. The density is: $\rho = 1790 - 1610\ kg/m^3$.

The heat and mass transfer has been studied in an absorber consisting of one vertical row of 10 horizontal copper tubes with a diameter of 12 mm outside and of 10 mm inside, and a length of 300 mm. The vertical pitch was 27 mm. The absorber was placed under a glass cap to allow flow observations. The measured data were: inlet and outlet temperatures and mass flows of the mixture, vapour and cooling water, vapour pressure and the inlet and outlet density of the mixture. These densities have been measured very accurately by a vibrating U-tube meter (reproducibility = ,01 kg/m^3). From these properties the mass fractions of the methanol have been derived.

A number of thermocouples were placed in the absorber to measure the mixture and cooling water temperatures in the flow direction and along the tubes. The operating conditions of the absorber were:

$w = 0,29 - 0,35$ kg/kg
$\theta = 30 - 60^{o}C$
$Re = \rho u\delta/\eta = 0,1 - 0,7$
$Pr = \nu/a = 60 - 220$
$Le = D/a = 0,0013 - 0,0054$

On those places, where thermocouples disturbed the flow, sometimes jets were observed. Apart from these spots the liquid feed was droplet wise at all flow rates within the operation conditions.

3. DESCRIPTION OF DROPLET FLOW

At the bottom of a tube at regular distances, $d = 2\pi\sqrt{\frac{2\gamma}{\rho g}}$, determined by the Tailor instability /5/, /6/, spots are situated from which droplets fall. The flow rate influences the fall frequency of these droplets.

The volume of the droplets is $V = k\left(\frac{\gamma}{\rho g}\right)^{1,5}$, where according to /7/, k = 14. Close up observations have been made by aid of a high speed camera at 1000 frames per second. A description resulting from these observations is given in figure 3.

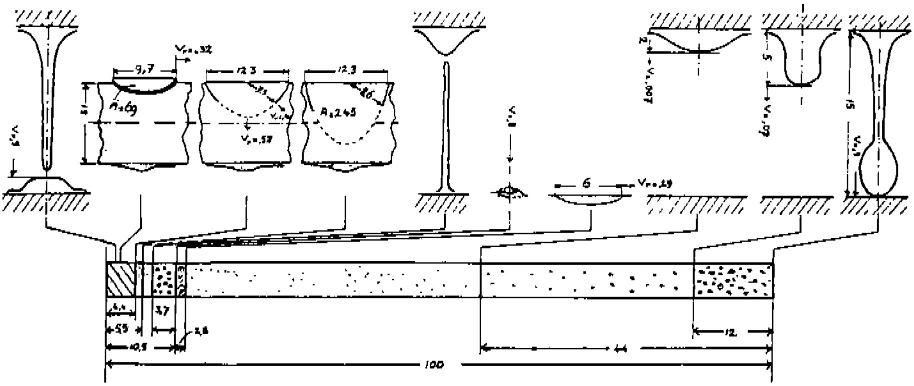


Fig. 3 - Hydrodynamics of a drop wise falling film on a relative time scale of 0 - 100. Distances and velocities in mm.

In this case the flow rate was per unit Γ_v = 3,3 mm^2/s, the mass fraction methanol w = 0,36 kg/kg and the temperature: v = 30 - 50°C. The time interval between the consecutive drops, 0,44 s, has been put at 100 in the figure. From t = - 0,12 to t = 0 a primary volume of 40 mm^3 falls at v = 0,3 m/s at the top of the tube. Between t = 0 and t = 0.06 the volume spreads out over an area: A = 250 mm^2; 37% of the area belonging to the droplet site. At that time the volume has 'disappeared' into the film, but still a liquid column is present between the tubes, that breaks up at t = 0,07, falling at t = 0,1 as a secundary volume of 10 mm^3 at v = 0,83 m/s on the tube, initiating a concentric ripple in the film. This ripple decayed at t = 0,13 at a radius of r = 3 mm.

Data, obtained from these observations are used in a hydrodynamic model of the flow. Film thickness and mean velocity from this model are plotted in figure 4 as a function of time and position and compared with results of stationary uniform sheet wise flow with $\delta = \sqrt[3]{\frac{3\,\nu\Gamma}{g\,\sin\theta}}$ and $\vec{u} = \frac{\Gamma}{\delta}$.

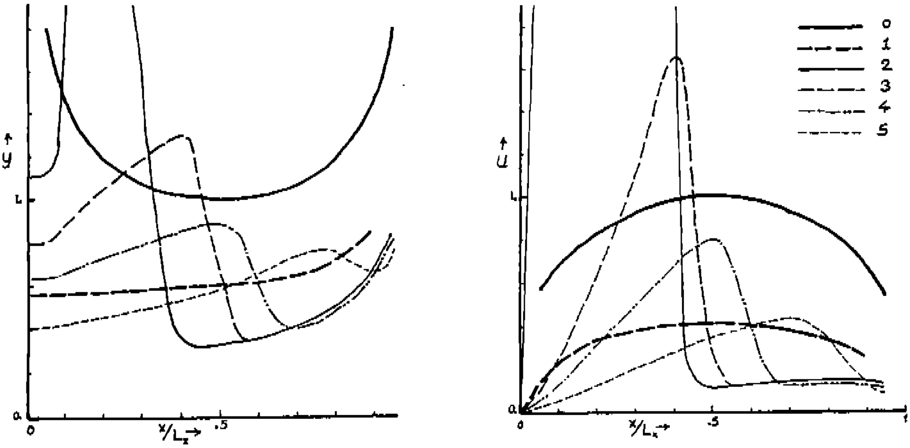


Fig. 4 - Relative film thickness Y and mean velocity U along the tube (top to bottom) 0: classical Nusselt results for smooth continuous feed; 1: time averaged results for droplet feed; 2: results at t = .007; 3: results at t = .037; 4: results at t = .109; 5. results at t = .367.

From the plot it becomes clear that the time averaged film thickness and the velocity are considerably lower than in the case of stationary liquid feed. It can be concluded also that the thin film is being swallowed by the pool in which the droplet spreads out. It is presumed that the phenomena taking place here, are comparable to those in the wavy flow of inclined thin film, although the flow phenomena are not as vigorous as in the wavy flow of inclined films /8, 9/.

4. HEAT AND MASS TRANSFER MODEL

The film thickness and the velocity on the tube are varying in time and in axial and tangential direction. A heat and mass transfer model, which takes the hydrodynamics fully into account, would be too complex. Therefore, we base our model on stationary smooth flow and try to summarize the hydrodynamics in empirically determined fitting parameters.

The Fourier number is almost immediately after the entrance of the droplet in the film, rather high, Fo >> .15. So, the entrance effects are negligible for the heat transfer.

The mass diffusion coefficient is about 500 times smaller than the heat diffusion coefficient, which means that even at the bottom of the tube the concentration boundary layer only is 10 to 20% of the filmthickness.

Our model has been based on the finite difference formulation of the conservation equations /4/. The film is split up into elements in the flow direction. For the conservation of mass in one element is found:

$$\dot{m}w + d\dot{m} = (\dot{m} + d\dot{m})(w + d\dot{m}) \approx \dot{m}w + wd\dot{m} + \dot{m}dw \qquad (1)$$

For the conservation of energy is written:

$$(\dot{m} + d\dot{m})(h + dh) - \dot{m}h \approx \dot{m}dh + hd\dot{m} = d\dot{m}h^{v} - dq_{w} \qquad (2)$$

These equations are solved by means of the von Kármán-Pohlhausen method: $\theta(y)$ and $w(y)$ are approximated by polynomials. The coefficients of the polynomials are found from the boundary conditions:

$$\theta(y) = a_1\left(\frac{y}{\delta}\right)^3 + a_2\left(\frac{y}{\delta}\right)^2 + a_3\left(\frac{y}{\delta}\right) + a_4 \qquad (3)$$

and

$$w(y) = b_1\left(1 - \frac{y}{\delta}\right)^2 + b_2\left(1 - \frac{y}{\delta}\right) + b_3 \qquad (4)$$

The velocity and the thickness of the smooth film are:

$$u = 3\,\bar{u}\,\left\{\frac{y}{\delta} - \frac{1}{2}\left(\frac{y}{\delta}\right)^2\right\};\quad \bar{u} = \frac{\Gamma v}{\delta} \qquad (5)$$

The boundary conditions are:

- y = 0 (tube wall):

$$\lambda\frac{\partial\theta}{\partial y} = \alpha_w(\theta_w - \theta_c);\quad \alpha_w = \left(\frac{d}{\lambda} + \frac{1}{\alpha_w}\right)^{-1}; \qquad (6)$$

$$\theta = \theta_w \qquad (7)$$

From the enthalpy equation $u\,\frac{\partial\theta}{\partial x} + v\,\frac{\partial\theta}{\partial y} = \lambda\,\frac{\partial^2\theta}{\partial y^2}$ follows because $u = 0$ and $v = 0$ at $y = 0$:

$$\frac{\partial^2\theta}{\partial y^2} = 0 \qquad (8)$$

- y = δ (interface mixture vapour):

There is a thermodynamic equilibrium.

$$\theta^{*} = \theta^{*}(w^{*},p) \qquad (9)$$

The interface conditions differ a little from those found by other authors. Since at the interface contrary to the bulk, the net mass flow is not zero, a drift flow has to be taken into account /10/.

$$d\dot{m} = -\rho\,D\,\frac{\partial w}{\partial y} + d\dot{m}w \rightarrow d\dot{m} = -\frac{\rho D}{1-w}\,\frac{\partial w}{\partial y} \qquad (10a)$$

$$dq = -\lambda \frac{\partial\theta}{\partial y} + d\dot{m}h_p = d\dot{m}h^v; \quad \lambda \frac{\partial\theta}{\partial y} = \frac{\rho D}{(1-w)} \frac{\partial w}{\partial y} (h^v - h_p) \tag{10b}$$

- $y = \delta(1-\delta_w)$ (border of the mass fraction boundary layer):

$$w = w_b \tag{11}$$

$$\frac{\partial w}{\partial y} = 0 \tag{12}$$

Because of the simplicity of the model, discrepancies with experiments will exist. This asks for the use of fitting parameters, preferably based on good experiments. The model has two outcomes, heat production and absorbed mass flow, so two parameters are to be used.

The mentioned swallowing-up of the thin film by the spreading out droplet is supposed to cause an enhanced mass transfer. Also already has been stated that the mean film thickness is lower than in the case of smooth stationary flow. The following equation can be written:

$$D = \epsilon_o D_o; \; D_o = kT/\eta \qquad k = 1,45.10^{-14} \tag{13}$$

$$\delta = \eta\delta_o \qquad \delta_o = \left(\frac{3\nu\Gamma}{g}\right)^{1/3} \tag{14}$$

The model is now evaluated by the experiments mentioned before. The results of this work will be presented at the meeting.

SUMMARY

A concise overview is given of different types of absorbers for thermal absorption cycles, leading to the conclusion that for viscous mixtures a dropletwise falling film over horizontal tubes might be a good design. Investigations on heat and mass transfer for such an absorber are described. A simplified computer model is developed, which is to be used with two empirical correlation parameters. Some model outcomes from experimental results are given. The model is a design tool for this type of absorbers.

NOMENCLATURE

a - thermal diffusion coefficient [m^2/s]
D - mass diffusion coefficient [m^2/s]
dm - vapour mass flow into an element [kg/s]
dqw - heat flow into the tube wall per element [w]
d_w - tube wall thickness [m]
g - gravitational acceleration [m/s^2]
h - mixture enthalpy [kJ/kg]
h^v - vapour enthalpy [kJ/kg]
h_p - partional methanol enthalpy in the mixture [kJ/kg]
$\dot{m}$ - mixture mass flow [kg/s]
p - vapour pressure [Pa]
u - film mean velocity [m/s]
y - co-ordinate perpendicular to the flow direction [m]
α - heat transfer coefficient [$W/m^2/K$]
γ - surface tension [N/m]
Γ_v - volume flow per wetted length [m^2/s]
δ - film thickness [m]
η - dynamic viscosity [kg/m/s]
θ - temperature [K]
λ - heat condictivuty [W/m/K]
ν - kinematic ciscosity [m^2/s]
ρ - density [kg/m^3]

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LES PHENOMENES DU TRANSFER DE CHALEUR ET DE MASSE D'UN ABSORBEUR A PELLICULE DESCENDANT EN GOUTELETTES SUR DES TUBES HORIZONTAUX.

RESUME: Une vue concise est présentée pour des types différents des cycles thermiques à absorption, ce qui, provoquant des mélanges visqueux une pellicule descendant en goutelettes sur des tubes horizontaux, pourrait être une bonne solution. On a écrit des recherches sur le transfer de chaleur et de masse pour un tel absorbeur. On a devéloppé un modèle pour ordinateur homologué àutiliser avec 2 paramètres de correlations empiriques. Des modèles établis à partir de recherches expérimentales sont indiqués. Le modèle est conçu pour ce type d'absorbeur.

THE PHENOMENONS OF HEAT AND MASS TRANSFER OF AN ABSORBER WHICH CHARACTERISTIC IS A FILM SLIDING DOWN IN LITTLE DROPS ON HORIZONTAL TUBES

SUMMARY

A concise view is presented for different types of absorption thermical cycles. The latter being the cause of viscous mixtures, a film, sliding down in little drops on horizontal tubes, could be a right solution. Studies have been written on the heat and mass transfer for such absorber. A model has been developed for computers authorized to be used with two parameters of empirical correlation. Models established from experimental researches are indicated. This model is conceived for this type of absorber.