Axial profiles of heat transfer coefficients in a liquid film evaporator

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Abstract: Regeneration is the most efficient way of managing used oil. It saves money by preventing costly clean-ups and liabilities associated with mismanagement of used oil and it also helps to protect the environment. A numerical study of the flow, heat and mass transfer characteristics of the vertical evaporating tube with the films flowing down on both the inside and the outside tube surfaces has been carried out. Condensation occurs along the outside wall surface and evaporation at the free surface of the inside film. The calculation domain of two film flow regions and tube wall is solved simultaneously. The longitudinal variation of temperature, mass flow rate, and hence the thickness of the films downward the tube can be obtained by applying conservation of the energy requirement to the differential element.

Keywords: liquid film, heat transfer, film evaporator

Introduction

Waste oils are dangerous for the environment and thus their regeneration is necessary. The aim of waste oils regeneration technologies is to maximise the rate of recycling at minimal financial cost and of course to lower the ecological impact. This means complex processing of mineral oils in order to achieve the recreation of all the oils properties, to the quality of fresh oil. Regeneration in practice takes place in conventional vacuum columns, similar to those used in petrochemical industry, or in vacuum evaporators with falling or wiped film evaporation. One of the developed methods is vacuum distillation of oils in thin falling oil film. In a falling film evaporator, a thin film of liquid generally flows downward under gravity on the inner surfaces of vertical tube bundles. Heat is transferred in order to increase the temperature of the liquid and/or to evaporate some of the liquid.

The heating medium is mostly steam condensing on the outer surfaces of the tubes. Occasionally, the falling film is cooled by heat removal. Advantages of falling-film equipment are (Frank et al., 1996): high values heat transfer coefficients, short residence times, short liquid holdup, low pressure drop.

Three dimensionless numbers suffice for the description of heat transfer.

- Nusselt number $$Nu = \frac{\propto}{\lambda}\left(\frac{\nu^2}{g}\right)^{\frac{1}{3}} \tag{1}$$
- Reynolds number $$Re = \frac{\dot{m}}{\mu} \tag{2}$$
- Prandtl number $$Pr = \frac{\nu}{a} = \frac{\mu c_p}{\lambda} \tag{3}$$

Term (ν^2/g) has the dimension of length and is used instead of the film thickness δ, because δ depends on Re. The wetting rate, $\dot{m}$, is the mass flow rate of liquid per unit of length of circumference. $\propto$ is the heat transfer coefficient, λ is the thermal conductivity, ν and μ is the kinematic and dynamic viscosity, respectively. c_p is the specific heat capacity and a is the thermal diffusivity of the liquid. In non-boiling falling films, all the physical properties (λ, μ, a, ν, c_p) were determined at the average of the inlet and outlet temperatures; in boiling films, they were obtained at the boiling temperature $t = t_{sat}(p)$.

Film thickness

The knowledge of the film thickness, δ, is required for the determination of the liquid holdup. It can be obtained from the Nusselt theory (Nusselt, 1916) if the film is smooth and laminar:

$$\delta_{lam} = \left(\frac{3\nu^2}{g}\right)^{\frac{1}{3}} Re^{\frac{1}{3}},\ Re < 400 \tag{4}$$

Kapitza (1948) recommended that the allowance for surface waves in laminar falling films is made by inserting the numerical value of 2.4 instead of 3 in equation (4). Brauer (1956) determined the following relationship for turbulent falling films using optical measurements:

$$\delta_{turb} = 0{,}302\left(\frac{3\nu^2}{g}\right)^{\frac{1}{3}} Re^{\frac{8}{15}},\ Re > 400 \tag{5}$$

Equation (5) agrees well with the results obtained from semi-empirical correlations derived from general laws on the velocity distribution (Kosky,1971; Kutateladze,1963; Portalski, 1963).

Materials and methods

In Fig. 1, the simplified layout of the laboratory equipment is shown. It fundamentally works as a vertical shell and tube heat exchanger.

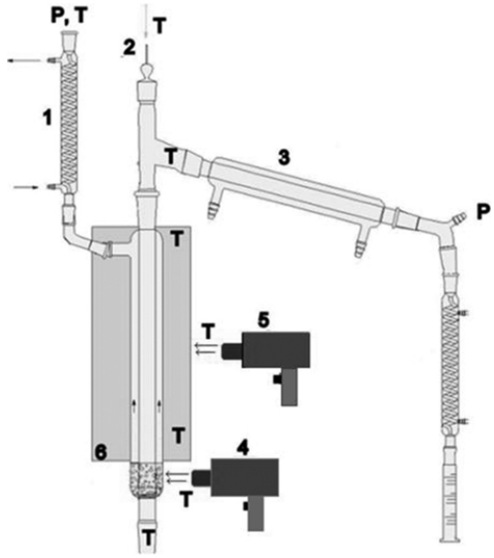

Fig. 1. Experimental equipment description.
1. Cooler of Dowtherm A, 2. Top cap of apparatus, 3. Oil cooler, 4. Heat gun for heating Dowtherm A, 5. Heat gun to compensate for heat loss from the system, 6. Glass case.

In Fig. 1, letter P shows the places used for pressure measuring, letter T shows the places where thermocouples were placed to measure the temperature.
Oil fed into the equipment was pre-heated by the initial laboratory temperature, to temperature close to its boiling temperature. Sensible heat used for this purpose was provided by heat guns located outside the body of the distillation equipment. Pre-heated oil was fed into the apparatus at varying flow rates by a peristaltic pump. Inside the device, the oil formed a falling film on the inner surface of the vertical tube. Uniform distribution of oil along the entire circumference of the inner tube surface was provided by a suitable distributor. Saturated vapours of Dowtherm A condensed on the outer surface of the tube and continued to heat the oil on the inner surface. Once the vapours of distilled oil get into the contact with the surface below their boiling temperature, they change their state of matter immediately.
The majority part of the equipment was made of glass, which has low heat conductivity, and therefore it decreases the overall heat transfer coefficient. However, since it was necessary to measure the behaviour of the system during the evaporation, this impact was negligible. High heat losses from the equipment were another issue during the experiment. The distillation device worked at temperatures of around 300 °C. To minimise these losses into the environment during the measurements, another outer glass tube was installed into the equipment. From the bottom of the device, heat required for the boiling of Dowtherm A was provided by a heat gun. Additional heat source was provided by another heat gun with heating regulation, which was blowing hot air at certain temperature between the apparatus and outer isolation. This was how the heat losses were reduced for the purpose of the experiment.

Mathematical model
Mathematical model of the device was based on the experimental equipment, Fig. 1, currently used in laboratory conditions. In Fig. 2, all phenomena considered in the mathematical model of the device are shown. Mineral oil was distributed on the inner surface of the inner tube, while heating medium was supplied into the shell side (space between the tubes) of the distillation device. Evaporated Dowtherm A was used as the heating medium, which forms a condensate on the outer surface of the inner tube at atmospheric pressure. Our model works with the assumption that the falling film of mineral oil is continuous. The thickness of the film slowly decreased due to oil evaporation. On the shell side, vapour of Dowtherm A was considered as saturated, so condensation only takes place during the heat transfer and a continuous film of liquid Dowtherm A is formed. Along the tube, the thickness of the film increased.

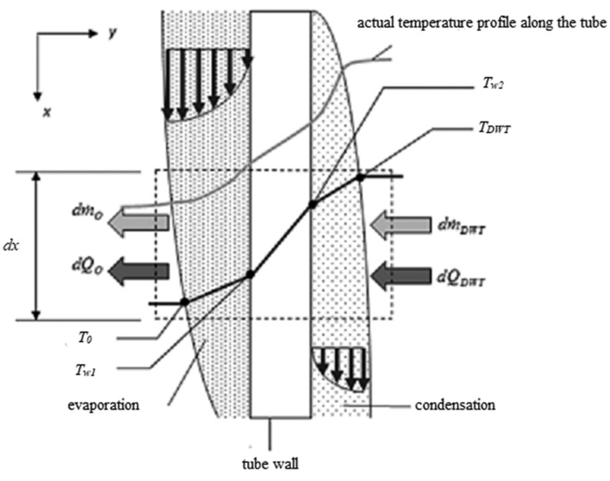

Fig. 2. Temperature profile along the vertical tube.

Mathematical model was created with the following assumptions:
1. Tube is divided into segments so that there is only laminar flow present. Temperature changes only along the tube and is constant in each section.

2. Condensing vapour of the heating medium is saturated; thus, only heat transfer caused by condensation takes place. Temperature of vapour in the heating medium is constant in the entire volume of the shell side.
3. Stress on the phase boundary is negligible.
4. Transfer of heat and momentum is provided only by convection, this means that only the advective factor is negligible.

For the flow analysis of the inner film of oil and outer film of Dowtherm A in a vertical tube evaporator, it is assumed that:

1. oil comes into the tube without turbulence,
2. thermodynamic properties of the fluids are constant in the operating range,
3. interfacial shear forces at the film free surfaces are negligible because the surrounding steam viscosities are much smaller than that of the liquid films,
4. saturated state is maintained at the free surface of the outer condensation film of Dowtherm A,
5. boundary-layer approximation is adopted for the governing equations of the flow and heat transfer because the films are very thin and the flow has a distinct main flow direction.

We divided the whole length of the evaporating tube into the same amount of equal segments of the length Δx and width W (circumference of the tube). We expect that in each of the segments, the mass of condensing vapor of Dowtherm A is $\Delta \dot{m}_{DWT}$. This causes an increase in the thickness of the film formed by the condensate of Dowtherm A. Heat $\Delta \dot{Q}$ given by the condensing vapor in a section of the column is used either to increase the temperature of the oil, or also (after temperature reaches the boiling temperature of oil) to evaporate a part of the liquid oil.

$$\begin{aligned}\Delta \dot{Q} &= \Delta_{evap} h_{DWT} . \Delta \dot{m}_{DWT} = \\ &= c_p . \Delta t \; . \Delta \dot{m}_{OIL} + \Delta_{evap} h_{OIL} . \Delta \dot{m}_{OIL,1}\end{aligned} \tag{6}$$

$\Delta_{evap} h_{DWT}$ is the specific evaporation heat of Dowtherm A, $\Delta_{evap} h_{OIL}$ is the specific evaporation heat of oil, c_p is the specific heat capacity of oil, $\Delta \dot{m}_{DWT}$ is the mass flow of saturated steam of Dowtherm A condensed in a balanced segment, Δt is the accruement of oil temperature in the balanced section (in case if the temperature of oil did not reach the boiling temperature), $\Delta \dot{m}_{OIL}$ is the actual amount of oil in a balanced section (whole amount of oil is heated up to boiling temperature), $\Delta \dot{m}_{OIL,1}$ is the mass flow of evaporated oil in a balanced segment.

Previously mentioned assumptions simply say that in case of steady state, heat flow through a phase boundary equals the conductive heat flow through a falling film of Dowtherm A of the thickness δ_{DWT}:

$$\Delta \dot{Q} = \Delta_{evap} h_{DWT} . \Delta \dot{m}_{DWT} = \lambda_{DWT} . \Delta x . W . \frac{T_{DWT} - T_{w2}}{\delta_{DWT}} \tag{7}$$

λ_{DWT} is the thermal conductivity of Dowtherm A, δ_{DWT} is the film thickness of Dowtherm A in a balanced segment, T_{DWT} is the temperature of the liquid film (condensate) of Dowtherm A, T_{w2} is the outside surface temperature of the tube wall.

Since all the calculations deal with the stationary state, heat flow continues through the wall of the tube into the film of boiling oil. These phenomena can be described by the following equations:

Heat transfer tube wall:

$$\Delta \dot{Q} = \lambda_W . \Delta x . W . \frac{T_{w2} - T_{w1}}{\delta_W} \tag{8}$$

and heat transfer through the film of oil:

$$\Delta \dot{Q} = \lambda_{OIL} . \Delta x . W . \frac{T_{w1} - T_{OIL}}{\delta_{OIL}} \tag{9}$$

λ_W is the thermal conductivity of the tube wall, λ_{OIL} is the thermal conductivity of liquid oil, T_{w1} is the inside surface temperature of the tube wall, T_{OIL} is the temperature of the liquid film of oil, δ_W is the thickness of the tube wall, λ_{OIL} is the film thickness of oil in a balanced segment.

The following iterative procedure of solving and updating was used:

1. Estimation of the heat amount provided by the heating agent Dowtherm A in a balanced segment. Given amount of heat is consumed by the oil film for heating up the oil to its boiling temperature and for evaporation of a part of it – see Eq. (6) using measured input temperature and mass flow rate of oil.
2. Second step is the decision step. It is necessary to determine whether the input temperature of oil to the balanced segment is lower or higher than the boiling temperature of oil.
3. If the observed temperature is lower, only heating of oil and no evaporation was observed in a balanced segment. If the observed temperature is higher, an appropriate amount of oil is evaporated and oil flows to the following segment at the boiling temperature.
4. Calculation of the heat amount for oil heating – see Eq. (6)
5. Calculation of the heat amount at the disposal for oil evaporation – see Eq. (6).
6. Calculation of the amount of evaporated oil – see Eq. (6).
7. Calculation of new thickness of the oil film – see Eq. (9).
8. Calculation of temperature T_{w1} – inner wall surface temperature of the tube (oil side) – see Eq. (9).

9. Calculation of temperature T_{w2} — outer wall surface temperature of the tube (side of Dowtherm A) — see Eq. (8).
10. Calculation of the condensed amount of Dowtherm A in a balanced segment — see Eq. (7).
11. Calculation of new film thickness of Dowtherm A — see Eq. (7).
12. Calculation of Dowtherm A steam temperature T_{DWT} from Eq. (7). This temperature is compared with the boiling temperature of Dowtherm A obtained from a database. If the temperatures are equal, iterative process is finished. If not, we have to repeat all steps from point 1.

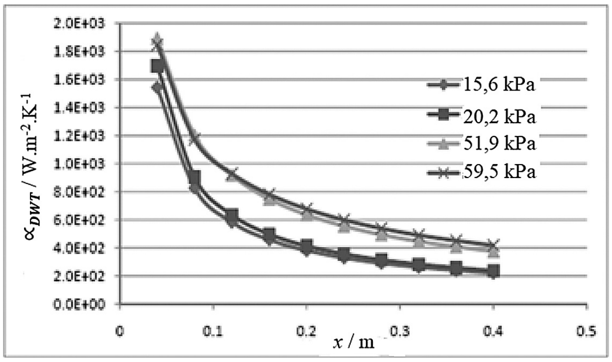

Fig. 3. Heat transfer coefficients $\propto_{DWT}$ of Dowtherm A along the vertical tube.

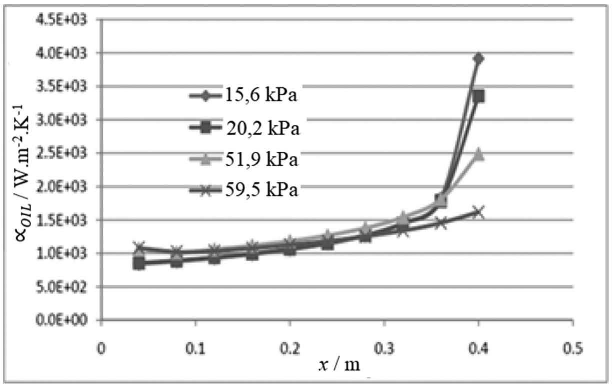

Fig. 4. Heat transfer coefficients $\propto_{OIL}$ of oil along the vertical tube.

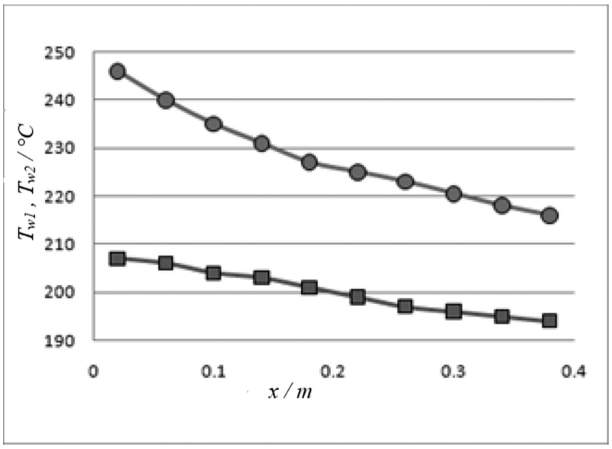

Fig. 5. Variation of the mean wall surface temperatures T_{w1} and T_{w2} along the tube axis direction for distillation pressure 20.2 kPa.

Results

Table 1 shows the measured mass flows of mineral oil which is supplied to the experimental laboratory equipment, $\dot{m}_F$, and the mass flows of distillate, $\dot{m}_D$. Temperatures in various points in the entire experimental device were measured using a system of thermocouples. Temperature on the site, where evaporation of oil takes place, was controlled by the pressure level altered using an oil vacuum pump. A heat gun with temperature regulation provided hot air into the space between the outer glass shell of the apparatus and the outer isolation. This helps to further reduce the heat loss from the shell side to minimum during the measurement.

Variation of the local convection coefficient of the inner and outer film along the tube axis direction for various evaporation pressures are shown in Figs. 3 and 4. From Fig. 3 it is evident that the decrease of heat transfer coefficient of Dowtherm A from values of thousands of W.m^{-2}.K^{-1} to values of hundreds. This effect is probably due to the rapid increase of the condensate liquid film thickness. On the other hand, the heat transfer coefficient of oil gently increased, which is the result of oil evaporation and the consequent decrease of oil film thickness.

Among the measured temperatures, the most important are the temperature of condensing Dowtherm A and that of oil vapours leaving the inner tube or wall temperatures in an appropriate place of condensation or evaporation. These temperatures are shown in Fig. 5 for the pressure of 20.2 kPa.

Table 1. Measured mass flows of oil feed and distillate

Measurement	1	2	3	4	5	6	7
$\dot{m}_F.10^4$/kg s^{-1}	1.43	1.05	1.09	1.27	1.43	1.87	1.87
$\dot{m}_D.10^4$/kg s^{-1}	1.26	1.03	0.95	1.14	1.16	1.72	1.58
yield/%	88.1	97.9	86.8	90.0	81.4	91.9	84.34

Conclusions

The developed mathematical model is based on the assumption that laminar falling films in the vertical direction are formed along the walls of the evaporator. Volumetric flow and temperature of waste oil fed into the device were measured before entering the evaporator. Temperature of oil vapours was measured by thermocouples placed inside the experimental device. Using the measured data we were able to calculate changes in the laminar film thickness as well as in the thickness of film formed by condensing Dowtherm A. The calculations were used to evaluate the heat transfer coefficients. These coefficients have crucial role in the falling film device design.
Our mathematical model is able to accurately describe processes in the falling film evaporator. Even though some model parameters had to be altered, the calculated yield of distillation was close to the measured one.

Acknowledgement
This article was created with the financial support from the Structural Funds of EU, project in progress: "Industrial research focused on material evaluation of liquid waste, mainly from the automotive industry", ITMS: 26220220074, is appreciated.

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