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MASS TRANSFER COEFFICIENT IN A TURBULENT VERTICAL ANNULAR TWO-PHASE FLOW

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ABSTRACT
The study is devoted to investigation of a turbulent annular vertical two-phase flow of air and water in adiabatic conditions and experimental determination of the mass transfer coefficient in a range of Reynolds numbers. A number of experiments were conducted to determine the effects of the water and air flow rates and air humidity on the evaporation of the water into the air. The results of the measurements are presented in the form of dimensionless Sherwood, Schmidt and Reynolds numbers. The experimental results are compared with existing correlations and new correlations for mass transfer coefficient are suggested based on fitting the experimentally obtained data.
Keywords: annular two-phase flow, mass transfer coefficient, correlation

1. INTRODUCTION
Turbulent heat and mass transfer are complex physical transport phenomena occurring in various engineering applications, such as boilers, condensers, heat exchangers, cryogenic technology, chemical and nuclear engineering. Methods based on the analogy between the transport of heat, mass and momentum in single-phase flows are commonly used to describe the same mechanisms in two-phase flows, although there is no experimental justification of the analogy. Measurements in two-phase flows are rather complex and there is still need to acquire new data to get a better insight in the liquid wall-film evaporation. Recent results for the droplet deposition in a two-phase flow are given in [1]. Mass transfer from the liquid wall-film to the air is highly affected by the liquid film free-surface waves [2,3,4]. However an exact theory describing the mechanisms of increasing the heat and mass transfer rates from an unordinary structure of the interface, or the effects of the liquid flow rates on the rate of evaporation, have not yet been developed [5]. Surface waves at the phase-interface are one of the important elements in annular two-phase flows, playing a major role in the interfacial heat, mass and momentum transport. The surface wave model in [6] shows wave profiles determined from the data of [7] in an annular vertical flow. The subject of the present study is experimental determination the mass transfer coefficient in a turbulent annular vertical two-phase flow.

2. EXPERIMENTAL SETUP
The experimental setup, built for investigations of heat and mass transfer in an annular flow is shown in Fig. 1 and detailed description is given in [8]. Basically it consists of two lines, the one for the gas

(air) and the other for the liquid (water) with all the necessary equipment for setting and regulation of a range of flow rates and pressures.

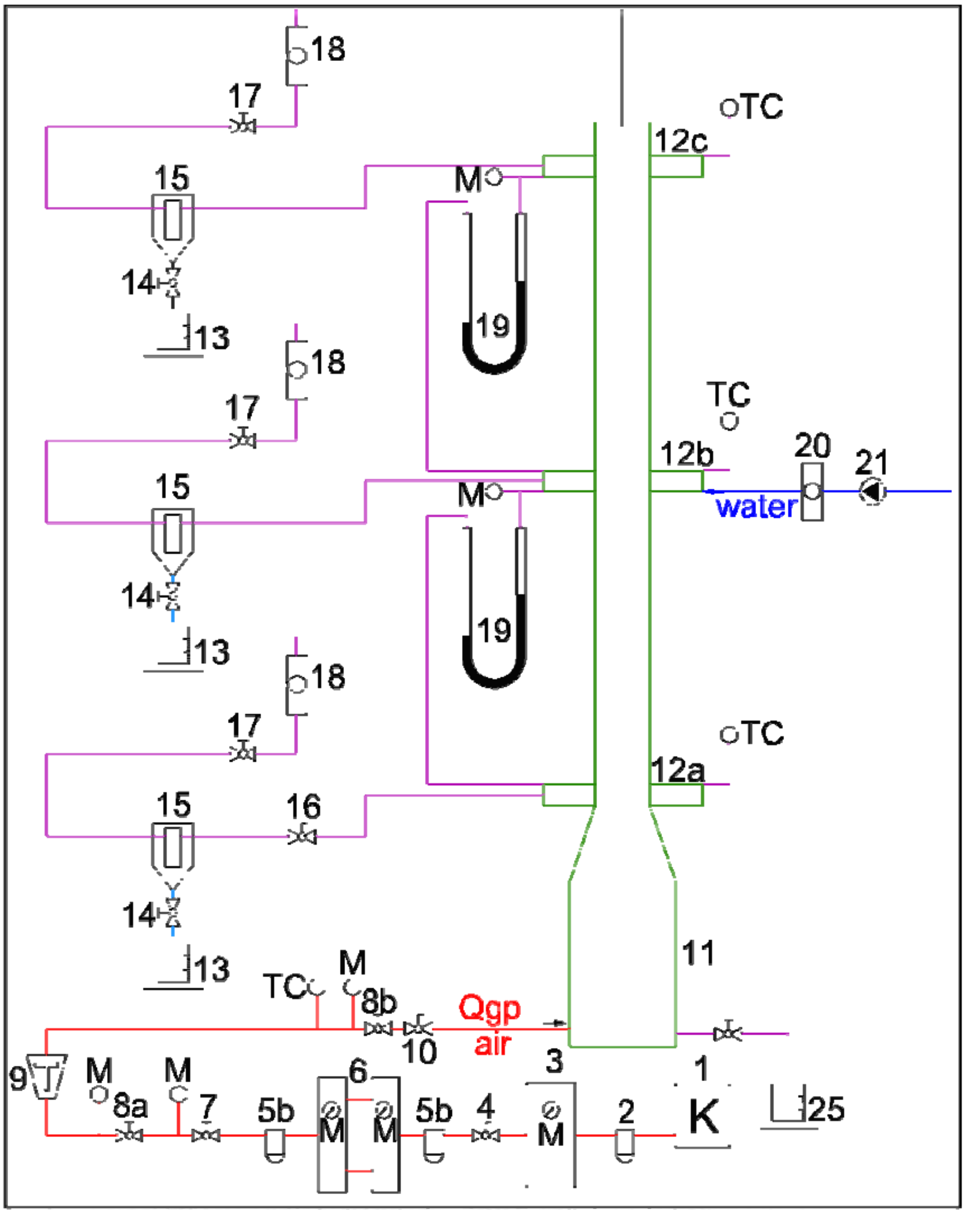

Figure 1. Schematic of the experimental setup: 1-Compressor, 2-Filter, 3-Air tank, 4-Faucet, 5-Filter, 6-Air dryer, 7-Pressure regulator, 8-Flow rate regulator, 9-Rotameter, 10-Faucet, 11-Inlet section, 12-Extractor, 13-Measuring vessel, 14-Valve, 15-Separator, 16-Cylindrical faucet, 17-Flow rate regulator, 18-Rotameter, 19-U-manometer, 20-Rotameter, 21-Gear pump, T-Termometer, M-Manometer, TC-Thermocouple

The experimental setup, built in the laboratory at the Faculty for Mechanical Engineering of the University of Sarajevo, is suitable for investigations of heat and mass transfer in two-phase flows for a relatively lower range of pressures and flow rates. It is designed to enable measurements in annular as well as dispersed two-phase flows. The setup consists of two similar sets: the one with tubes made from Plexiglas for the determination of mass transfer coefficient in the annular flow with visual monitoring, and the other with tubes made of stainless steel where heat transfer and drop deposition can be investigated in addition to mass transfer. The setup enables measuring the flow parameters at the inlet and the outlet of the test section, such as pressure, gas and liquid flow rate and gas relative humidity, used to determine the values for the mass transfer coefficient.

3. RESULTS

The correlation for the mass transfer coefficient is obtained under the assumption of a dilute solution of water vapor in air. Therefore it is justifiable to assume that the air flow rate at the inlet remains approximately constant. Under adiabatic conditions the pressure will not change and therefore Reynolds and Schmidt numbers will remain constant along the test section yielding constant values for the mass transfer coefficient. Furthermore, due to dilute solution, it is assumed that the mass transfer coefficient will have a linear dependence on the vapor concentration difference as a driving force for evaporation. With the aforementioned assumptions and applying stationary material balance for water in a small segment of the wetted test section and with constant molar flux of air, the correlation is suggested in [8] for the mass transfer coefficient of the form $\mathrm{Sh} = f\left(\mathrm{Re},\mathrm{Sc}\right)$ as follows

$$\mathrm{Sh} = \frac{D}{4L}\mathrm{Re}\,\mathrm{Sc}\ln\left(\frac{p_A - p_{Ain}}{p_A - p_{Aout}}\right), \qquad \text{... (1)}$$

where Sh, Re and Sc are Sherwood, Reynolds and Schmidt number, respectively, D and L are the diameter and length of the test section, respectively, p_A is the partial vapor pressure in air, with values p_{Ain} and p_{Aout} at the inlet and the outlet of the test section, respectively. By measuring the parameters determining the Sherwood number in Eq. (1) using the described experimental setup the values for the mass transfer coefficient are determined. All relevant details on the derivation of Eq. (1), based on the theoretical considerations of [9] can be found in [8]. The measurements were performed twofold: with a constant air flow rate and variable water flow rate, and vice versa. The results are presented in Figs. 2 to 5 for Reynolds numbers of the air in a range from 11000 to 18500.

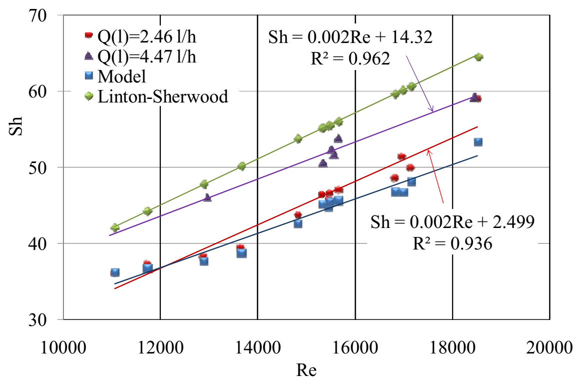

Figure 2. Experimentally obtained Sherwood number and comparison to the model Eq. (1) at different air Reynolds numbers

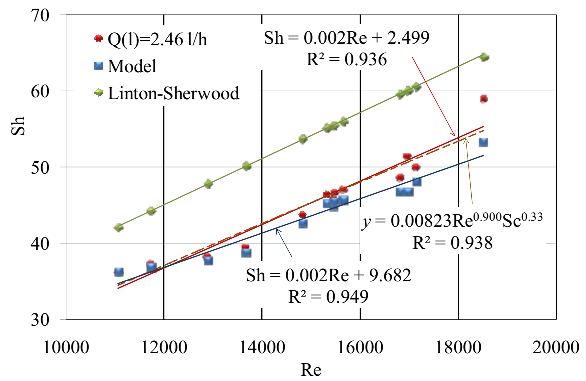

Figure 3. Comparison of the experimentally obtained Sherwood number at Q_l=2.46 l/h with the existing correlation [10]

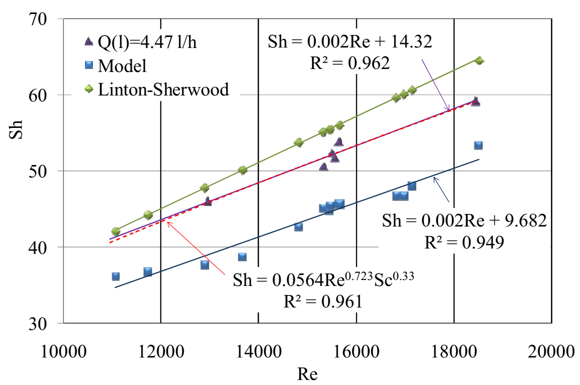

Figure 4. Comparison of the experimentally obtained Sherwood number at Q_l=4.67 l/h with the existing correlation [10]

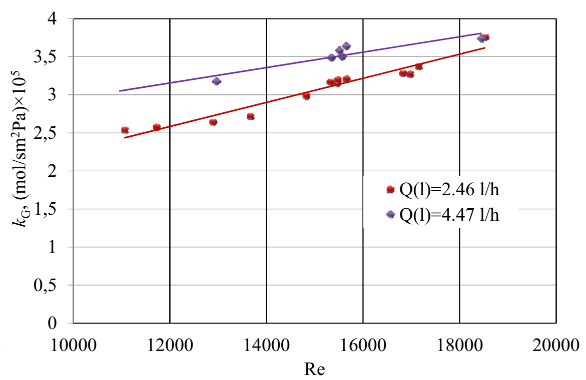

Figure 5. Experimentally obtained values for the mass transfer coefficients at different air Reynolds numbers

As expected the mass transfer increases with increasing the Reynolds number of the air flow. Mass transfer is increased also if the air is dryer due to greater evaporation rate. The obtained values for the Schmidt number are in the range between 36 and 45 in the range of Reynolds numbers from 11000 to 18500. According to the form of the existing correlations, the experimental data obtained at water flow rates of 2.46 l/h and 4.47 l/h was fitted to yield the following correlations

$$\begin{aligned} \mathrm{Sh} &= 0.00823\,\mathrm{Re}^{0,900}\,\mathrm{Sc}^{0,33},\ \text{for } Q_l = 2.46\ \mathrm{l/h} \\ \mathrm{Sh} &= 0.00564\,\mathrm{Re}^{0,723}\,\mathrm{Sc}^{0,33},\ \text{for } Q_l = 4.47\ \mathrm{l/h} \end{aligned} \quad \ldots (2)$$

The results show some discrepancy between the experimentally obtained values for Sherwood number and those obtained by the theoretical model Eq. (1). This difference is due to the fact that the liquid film in the test section is covered with surface waves, rather than being smooth as the theory suggests. Comparing the obtained values for Sherwood number in Eq. (2) with the correlation Linton-Sherwood [10] it is seen that the Linton-Sherwood correlation yields somewhat greater values. The difference is about 21% at water flow rate of 2.46 l/h and Reynolds number of 11000, and about 13% at water flow rate of 4.47 l/h and Reynolds number of 18500. Finally, for all measurements error analysis has been conducted to assess the reliability of the measured values and errors were determined to be within the range of 12% maximum.

4. CONCLUSIONS

Turbulent annular vertical two-phase flow of air and water in adiabatic conditions was investigated experimentally to determine the mass transfer coefficient in a range of Reynolds numbers. The experimentally obtained results for the mass transfer coefficient, presented in the form of dimensionless Sherwood, Schmidt and Reynolds numbers, were compared with the existing correlations. In addition, data fitting yielded new correlations for the mass transfer coefficient. The theoretical correlation for Schmidt number underpredicts the experimental results for the mass transfer coefficient, because the liquid film is not smooth in the test section, as assumed in the derivation of the model, but is covered with surface waves yielding greater measured values.

5. REFERENCES

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