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TRANSIENT NATURAL CONVECTION HEAT AND MASS TRANSFER DURING REFRIGERATION OF AIR BY HORIZONTAL TUBES

M. K. EL-RIEDY
Mechanical Engineering Department, Al-Azhar University, Cairo, Egypt

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Abstract—Experiments were carried out on transient heat and mass transfer by natural convection during refrigeration of air by horizontal tubes in the range 10^3–10^6 for *Gr Pr* and *Gr Sc*. The heat and mass transfer coefficients during the period of refrigeration were studied. The time required from the moment of starting refrigeration of air until approaching constant values of heat and mass transfer coefficients was obtained.

NOMENCLATURE

A surface area of tube [m^2]
C_0 concentration in bulk
C_s concentration at tube surface
C_p specific heat of moist air [J kg^{-1} K^{-1}]
C_{pe} specific heat of the ethylene glycol [J kg^{-1} K^{-1}]
d tube diameter [m]
D diffusion coefficient [m^2 s^{-1}]
g gravity acceleration [m s^{-2}]
Gr Grashof number, $g\Delta\rho d^3/\gamma^2\rho$
h_h heat transfer coefficient at any time [W m^{-2} K^{-1}]
$h_{h,a}$ average heat transfer coefficient during refrigeration [W m^{-2} K^{-1}]
h_m mass transfer coefficient at any time [kg m^{-2} s^{-1}]
$h_{m,a}$ average mass transfer coefficient during refrigeration [kg m^{-2} s^{-1}]
k thermal conductivity [W m^{-1} K^{-1}]
L latent heat [J kg^{-1}]
Le Lewis number, $h_h/h_m C_p$
m flow rate of the ethylene glycol [kg s^{-1}]
Nu Nusselt number, $h_{h,a}d/k$
Pr Prandtl number, $C_p\mu/k$
q_{lat} latent heat transfer [W]
q_{rad} heat transfer by radiation [W]
q_{sen} sensible heat transfer [W]
q_{tot} total heat transfer [W]
Sc Schmidt number, ν/D
Sh Sherwood number, $h_{m,a}\, d/\rho D$
t_1 inlet temperature of the ethylene glycol [°C]
t_2 outlet temperature of the ethylene glycol [°C]
t_0 bulk temperature [°C]
t_s average surface temperature of tube [°C]
w rate of condensed water or sublimed snow [kg s^{-1}].

Greek symbols
ψ relative humidity of air [%]
μ dynamic viscosity [kg m^{-1} s^{-1}]
ν kinematic viscosity [m^2 s^{-1}]
ρ density [kg m^{-3}]
$\Delta\rho$ density difference between bulk and tube surface due to the combined effects of partial pressure and temperature [kg m^{-3}]
τ time [min].

INTRODUCTION

TRANSIENT heat and mass transfer by natural convection during refrigeration of air by horizontal tubes is used in many practical applications in refrigeration and air conditioning. There is no available data for the variation of the heat and mass transfer coefficient values during the refrigeration process. The only data available are on the average values of heat and mass transfer coefficients during the period of refrigeration. The present research work was carried out to study the variation of heat and mass transfer coefficients during the refrigeration period.

SUMMARY OF PREVIOUS WORK

Heat and mass transfer for air flowing over a disc with snow formation was studied by Yavnel [1]. Three equations were presented: for sensible heat transfer at the point of snow formation on the disc surface, for heat transfer to the disc in the absence of mass transfer and for mass transfer. An analogy between the heat and mass transfer mechanisms in the refrigeration of air was suggested.

Kennedy and Goodman [2] studied free convection heat and mass transfer under conditions of frost deposition on a vertical surface. The local heat and mass transfer coefficients from humid air to the frost surface were obtained along with the effective thermal conductivity and density of the frost. An interferometer was used to determine the temperature distribution in the boundary layer adjacent to the frost surface to allow local values of the heat flux to be calculated. Observations of the frost structures were made. It was concluded that the effective heat and mass transfer surface area was increased due to the porous structure of the frost layer thus causing the apparent heat and mass transfer coefficients to increase with time.

Wragg and Nasiruddin [3] correlated mass transfer by free convection under the influence of simultaneous thermal convection for upward facing horizontal disc electrodes.

Schutz [4] also used an electrochemical method to study mass transfer at spheres and horizontal cylinders by natural convection.

El-Riedy [5] suggested dimensionless equations for both the average heat (sensible) and mass transfer by natural convection from air to horizontal tubes. The analogy between heat and mass transfer was also verified.

Okada [6] investigated freezing around two cooled pipes in cross-flow through a porous medium. Within the range of the validity of Darcy's law, a numerical analysis of this process of two-dimensional (2-D) growth under the assumption of quasi-steady state was presented. The rate of growth of the frozen regions, the changes of the shape of the frozen regions, the amount of heat transferred to the freeze-pipes, and the time required for closure of the frozen regions were obtained. The time interval was chosen to be short in the initial period of freezing because the rate of growth was high.

Cremers and Mehra [7] studied experimentally frost growth on a cooled vertical cylinder in free convection flow. A correlation that was based on heat transfer considerations was found to be effective in predicting frost growth rates particularly at relative humidities equal to or greater than 65% and growing times equal to or greater than 60 min.

There is no available data, as far as the author knows, for the effect of time on the values of the heat and mass transfer coefficients during refrigeration of air by horizontal tubes. The aim of the work reported in this paper was to study this effect.

APPARATUS

Figure 1(a) depicts the apparatus used. It consisted essentially of an experimental tube (1) cooled by ethylene glycol at atmospheric pressure. The tube was mounted horizontally above a bench by two legs which were located near the entrance and the exit of the tube to avoid end effects. The ethylene glycol was circulated by a pump (2) and entered the tube at a constant temperature achieved by means of a thermostat (3). Two mechanical vapour compression refrigeration units (4) and (5) were used for cooling the ethylene glycol. The minimum temperature on the surface of the tube was 255 K. The rate of flow of ethylene glycol was adjusted by a valve (6) to give a nearly constant temperature on the surface of the tube. The air inside the experimental tube was removed from the upper point by using a valve (7).

The discharge rate of the ethylene glycol was measured by a flow meter (8). The surface temperatures of the tube were measured by nine thermocouples which were located at different locations on the tube

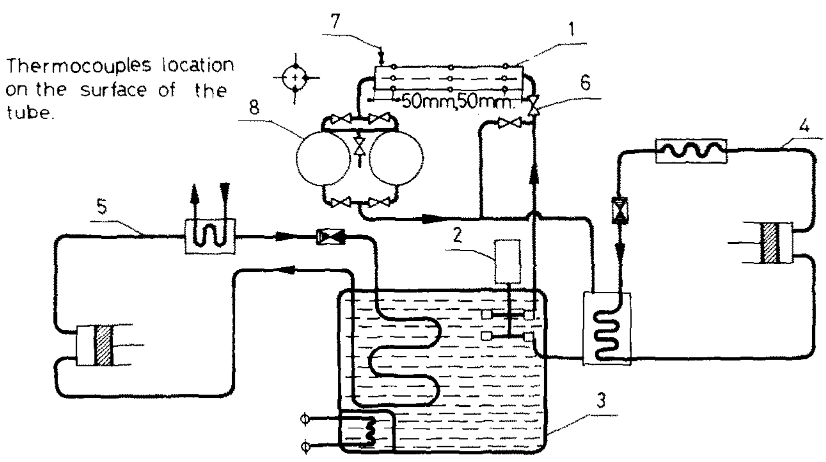

FIG. 1(a). Diagrammatic sketch of apparatus.

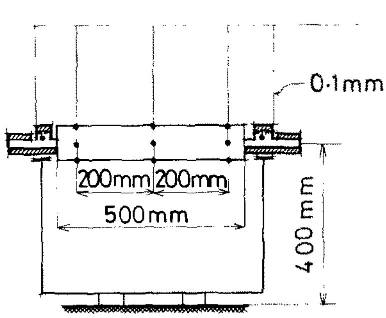

FIG. 1(b). Experimental tube and thermocouple locations.

surface (not the frost surface) as shown in Fig. 1(b). The maximum variation in surface temperature of the tube was about 1.6°C and the mean surface temperature was assumed to be equal to the average of those measured. The drop in temperature of the ethylene glycol through the tube was measured by a differential thermocouple; the two junctions of this thermocouple were located at the inlet and the outlet of the tube. The tube and the condensed water or the sublimed snow on the surface were also weighed by means of a sensitive balance at different time intervals. Knowing the weight of the dry tube enabled the weight of the condensed water or the sublimed snow to be estimated. The experiments were carried out in a closed large room to ensure freedom from draughts.

Two tubes of 500 mm in length were used. The first tube was 20 mm in diameter and made of brass with a polished bright surface while the second tube was 56.6 mm in diameter and made of steel with a nickel surface. The emissivity of the surfaces of both tubes during heat transfer accompanied by condensation of water vapour was taken, from ref. [8], as 0.95, while their emissivities in heat transfer accompanied by sublimation of water vapour was taken, from ref. [9], as 0.85.

The surface temperature of the tube was varied to allow the study of two different cases of heat and mass transfer. These were:

(1) Sensible heat transfer accompanied by latent heat transfer due to condensation of water vapour on the surface of the tube was obtained when the surface temperature of the tube was less than the dew point temperature of the air but higher than 0°C.

(2) Sensible heat transfer accompanied by latent heat transfer due to sublimation of water vapour on the surface of the tube was obtained when the surface temperature of the tube was less than the dew point temperature of the air and lower than 0°C.

RESULTS AND DISCUSSION

Mass transfer

The weight of the condensed water or sublimed snow on the surface of the tube at different time intervals enabled the coefficient of mass transfer by convection to be calculated as

$$w = h_m A(C_0 - C_s). \quad (1)$$

The concentration of water vapour C_s in this equation was calculated corresponding to the tube surface temperature instead of the frost temperature. The thickness of the frost in the experiments was less than 1 mm, hence the difference between the frost surface temperature and the tube surface temperature might not exceed 2°C. The concentration of saturated water vapour in air at a low range of temperatures was not affected by this small temperature difference. Thus the error in the concentration difference $(C_0 - C_s)$ due to this assumption did not exceed 4%.

Figure 2 shows some results obtained for the variation of the mass transfer coefficient for the 56.6 mm horizontal tube with the time from the beginning of the refrigeration process. It is clear that the values of the mass transfer coefficients increase to a maximum and then decrease to constant values. The maximum values of the mass transfer coefficients are 9–15% higher than the constant values of the mass transfer coefficients. The mean values of the mass transfer coefficients are almost equal to or a little more than the constant values of the mass transfer coefficients (exceeding them by no more than 4% over the period of measurement).

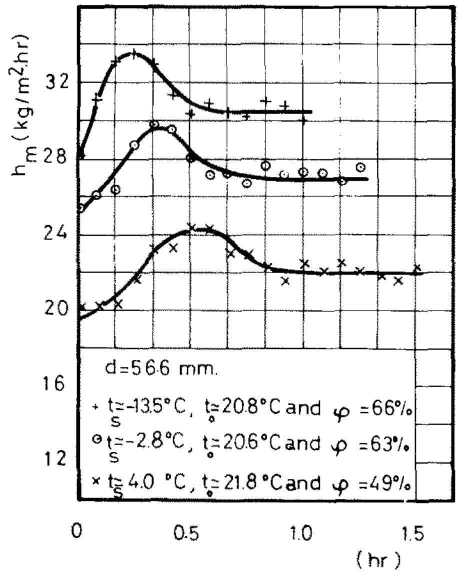

FIG. 2. Variation of mass transfer coefficient with time.

Heat transfer

The rate of heat loss from the tube at different time intervals was determined by the equation

$$q_{tot} = mC_{pe}(t_1 - t_2). \quad (2)$$

Corrected for radiation q_{rad} (which represented about 20% of the total heat) and latent heat due to mass transfer q_{lat} the coefficient of heat transfer (sensible) by convection at any time could be calculated as

$$q_{sen} = q_{tot} - q_{rad} - q_{lat}, \quad (3)$$

$$= h_h A(t_0 - t_s), \quad (4)$$

where

$$q_{lat} = wL. \quad (5)$$

To the author's knowledge, the emissivity values given in refs. [8, 9] are the best available in the literature. However, it should be noted that if there were an error of say 20% in the emissivity values, the maximum error in the calculated heat transfer coefficients would be less than 5%.

Figure 3 shows some results obtained for the variation of the heat transfer coefficient for the 56.6 mm horizontal tube with the time from the beginning of the

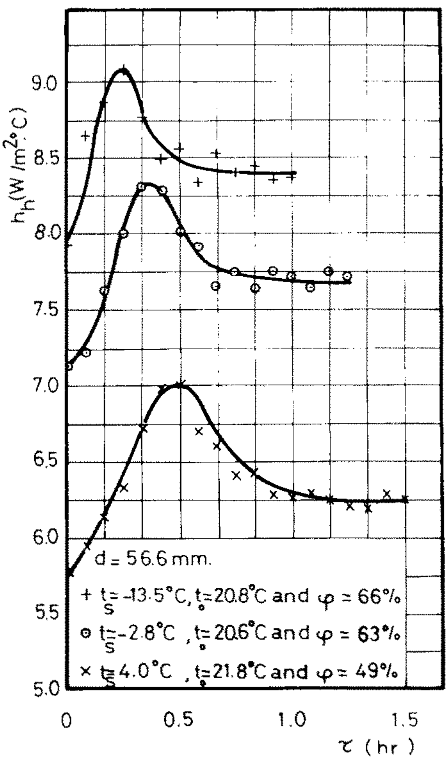

FIG. 3. Variation of heat transfer coefficient with time.

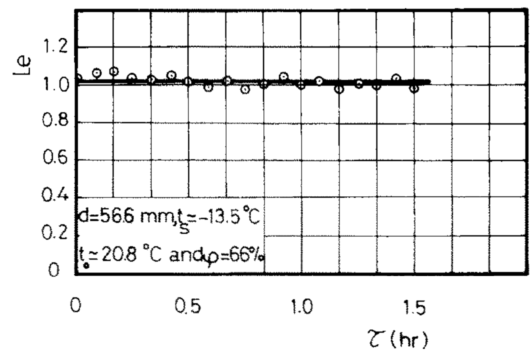

FIG. 4. Variation of Le with time.

refrigeration process. It is clear that the calculated heat transfer coefficient between the tube surface and the air includes the effect of the two thermal resistances of the frost and the air because the temperature difference between the tube surface and the ambient air is taken. Thus, the variation of the thermal resistance of the frost was taken into consideration in calculating the overall coefficient of heat transfer between the tube surface and the air. The values of the heat transfer coefficients (sensible) increase up to a maximum then decrease to constant values. The maximum values of heat transfer coefficients (sensible) are 10–14% higher than the eventual values of the heat transfer coefficients. The mean values of the heat transfer coefficients (sensible) do not exceed 3% higher than the constant values of the heat transfer coefficients over the period of measurement.

Heat transfer without mass transfer

A set of experiments was also carried out on natural convection from the two horizontal tubes without mass transfer. All results were represented by one straight line with a slope equal to 0.25 (indicating the laminar region). The laminar heat transfer ($Gr\ Pr$ from 2×10^3 to 10^6) was represented, within $\pm 7\%$ by

$$Nu = 0.57(Gr\ Pr)^{0.25}. \tag{6}$$

The emissivity of the polished bright brass tube and of the nickel-surfaced steel tube in the dry heat transfer were taken from Perry [8] as 0.023 and 0.045, respectively. The radiation in the heat transfer without mass transfer represented less than 5% of the total heat. So, the radiation in the dry heat transfer is very small if compared with the heat transfer accompanied by mass transfer. Condensation or sublimation of water vapour on the tube surface changes the condition of the surface and hence increases the emissivity.

Equation (6) gives values of heat transfer coefficients 7% higher than the published values in the literature for dry heat transfer from horizontal tubes.

Analogy between heat and mass transfer

Figure 4 shows the variation of Lewis number with time during a refrigeration process. The average value of the Lewis number is 1.02 with an error of $\pm 4\%$. Thus lending evidence for the analogy between heat and mass transfer during the refrigeration processes in the conditions used in the experiments. The Lewis number can be taken as unity at any time to a good approximation.

Variation of required time for constant coefficients with Gr

Figure 5 shows the variation of the time required for approaching constant values of heat transfer coefficients and mass transfer coefficients (the approach time, τ_0) against the mean values of log Gr. The results in the range 10^3–10^6 for $Gr\ Pr$ and $Gr\ Sc$ can be represented, within $\pm 17\%$, by

$$\tau_0 = 3.45 - \log Gr^{0.5}. \tag{7}$$

It is clear that the approach time decreases with increase of Gr values and hence with increase of heat and mass transfer coefficients.

EXPLANATION OF THE RESULTS

Heat transfer accompanied by mass transfer is a complicated process in which a variety of heat and mass transfer mechanisms are at work simultaneously. The formation of frost on a surface is usually idealized as a moving boundary problem where heat and mass transfer occur across the boundary layer to the growing frost layer. The time scales associated with heat and mass transfer within the frost layer are such that the boundary layer can be considered quasi-steady in

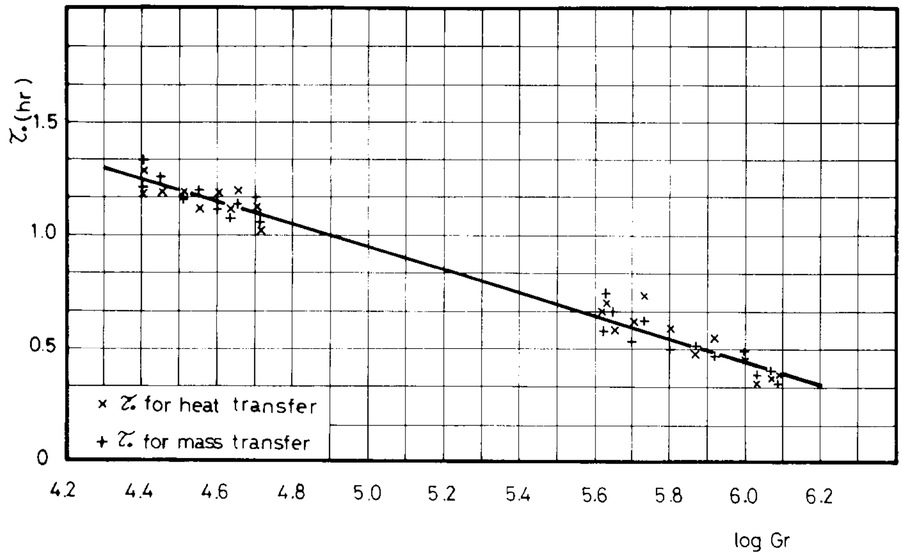

FIG. 5. Variation of the approach time τ_0 with log *Gr*.

relation to it. The heat and mass transfer coefficients increase initially because the rough surface presents a larger surface area for heat and mass transfer. The heat and mass transfer coefficients decrease after the initial increase and then remain constant.

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CONVECTION NATURELLE VARIABLE DE CHALEUR ET DE MASSE PENDANT LA REFRIGERATION D'AIR PAR DES TUBES HORIZONTAUX

Résumé—Des expériences portent sur le transfert variable de chaleur et de masse par convection naturelle pendant la réfrigération d'air par des tubes horizontaux dans le domaine 10^3–10^6 pour *Gr Pr* et *Gr Sc*. Les coefficients de transfert thermiques et massiques pendant la période de réfrigération sont étudiés. On obtient le temps nécessaire entre le début de la réfrigération de l'air et l'obtention de valeurs constantes des coefficients de transfert.

INSTATIONÄRE FREIE KONVEKTION—WÄRME- UND STOFFÜBERGANG WÄHREND DER ABKÜHLUNG VON LUFT AN WAAGERECHTEN ROHREN

Zusammenfassung—Für Wärme- und Stoffübergang bei instationärer freier Konvektion während der Abkühlung von Luft an waagerechten Rohren wurden Experimente im Bereich von 10^3–10^6 für *Gr Pr* und *Gr Sc* durchgeführt. Während der Abkühlung wurden Wärme- und Stoffübergangskoeffizienten untersucht. Die benötigte Zeit vom Beginn der Abkühlung bis zum Erreichen konstanter Werte für den Wärme- und Stoffübergang wurde ermittelt.

ТЕПЛО- И МАССОПЕРЕНОС В УСЛОВИЯХ ПЕРЕХОДНОЙ ЕСТЕСТВЕННОЙ КОНВЕКЦИИ ПРИ ОХЛАЖДЕНИИ ВОЗДУХА ГОРИЗОНТАЛЬНЫМИ ТРУБАМИ

Аннотация—Проведено экспериментальное исследование тепло- и массопереноса в условиях переходной естественной конвекции при охлаждении воздуха горизонтальными трубами в диапазоне значений критериев $Gr\ Pr$ и $Gr\ Sc$ от 10^3 до 10^6. Изучено изменение коэффициентов тепло- и массопереноса в течение периода охлаждения, а также определено время от начала охлаждения воздуха до достижения коэффициентами тепло- и массопереноса постоянных значений.