Int. J. Heat Mass Transfer. Vol. 30, No. 4, pp. 807–809, 1987
Printed in Great Britain

0017–9310/87 \$3.00 + 0.00
Pergamon Journals Ltd.

TECHNICAL NOTES

Heat or mass transfer adjacent to the free end of a rotating cylinder

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(*Received* 17 *July* 1986 *and in final form* 2 *October* 1986)

INTRODUCTION

HEAT and mass transfer at rotating cylinders has been widely investigated for several decades, as witnessed by a broad literature of which refs. [1–3] are representative for heat transfer and refs. [4, 5] are representative for mass transfer. That work was concerned with the average transfer characteristics of the cylinder, and local coefficients and their possible spatial variations have not been heretofore investigated. In this study, consideration is given to a rotating cylinder having a free end, the objective being to measure the variation of the transfer coefficient as a function of the distance from the end. In particular, the extent of the end-affected region of the cylinder will be determined.

To facilitate the work, the experiments were performed for mass transfer rather than heat transfer, with the naphthalene sublimation technique being used. The experiments were carried out for rotational Reynolds numbers ranging from 700 to 10,000. The cylinder was situated in air in spacious surroundings which, aside from the fluid motions induced by the rotation, was otherwise quiescent.

Prior to the main body of experiments aimed at determining the end-adjacent mass transfer variations along the cylindrical surface, supplementary experiments were performed to measure the mass transfer at the end face of the cylinder [6]. The data from the supplementary experiments are presented in Fig. 1 in terms of the end-face Sherwood number Sh_{end} plotted vs the Reynolds number Re, respectively defined as

$$Sh_{\text{end}} = K_{\text{end}}D/\mathscr{D}, \quad Re = UD/\nu \tag{1}$$

where U is the velocity at the outer rim of the face

$$U = (D/2)\omega. \tag{2}$$

The mass transfer coefficient K_{end} is the average value for the end face as a whole, and Sh_{end} has a similar meaning. The low Reynolds number data (700–800) were obtained with a 2.54 cm diameter cylinder, while the other data were obtained with a 3.686 cm diameter cylinder. As in the main experiments, naphthalene sublimation was also used in the supplementary experiments.

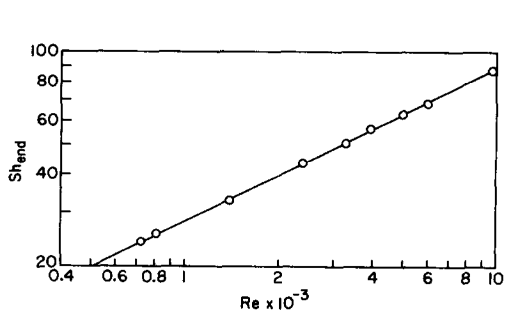

FIG. 1. Average Sherwood numbers at the face of the free end of a rotating cylinder (from ref. [6]).

Also appearing in Fig. 1 is a straight line which represents the analytical prediction of the average Sherwood number for a rotating disk [7]. The prediction pertains to a Schmidt number of 2.5 (naphthalene sublimation in air) and is expressed by the following equation

$$Sh_{\text{end}} = 0.884Re^{1/2}. \tag{3}$$

As seen in the figure, excellent agreement prevails between the end-face data and the predictions for the disk. This finding indicates that mass or heat transfer from the end face of a rotating cylinder can be evaluated from rotating disk predictions, which are available for all Schmidt and Prandtl numbers [7]. The excellent agreement also lends confidence to the experimental technique used here.

EXPERIMENTS

The apparatus used for the main experiments is shown in a longitudinal sectional view in Fig. 2. The major components of the apparatus included: (a) an array of naphthalene-coated test elements, (b) a Delrin shaft which housed the test elements, (c) a steel coupling which connected

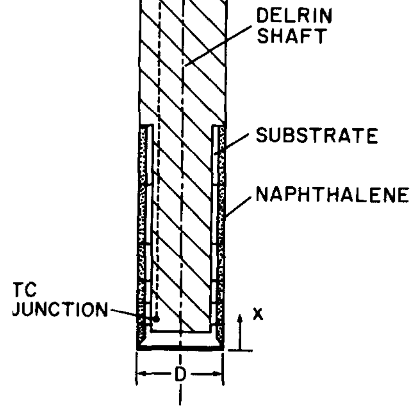

FIG. 2. Experimental apparatus.

NOMENCLATURE

- A per-element mass transfer area
- D diameter of cylinder
- $\mathscr{D}$ mass diffusion coefficient
- K per-element mass transfer coefficient
- K_{end} average mass transfer coefficient at the end face of the cylinder
- $\dot{M}$ per-element rate of mass transfer
- Re rotational Reynolds number, UD/ν
- Sc Schmidt number
- Sh per-element Sherwood number, $KD/\mathscr{D}$
- Sh_{end} average Sherwood number at the end face of the cylinder, $K_{end}D/\mathscr{D}$
- x axial coordinate (Fig. 1)
- U circumferential velocity at the surface of the cylinder, $(D/2)\omega$.

Greek symbols
- ν kinematic viscosity
- ρ_{nw} naphthalene vapor density at subliming surface
- $\rho_{n\infty}$ naphthalene vapor density in surroundings
- ω angular velocity.

the Delrin shaft to the source of rotation, and (d) a vertical milling machine (not shown) with whose spindle the steel coupling was mated. As seen in the figure, the mass transfer elements and the Delrin shaft formed a free-ended, uniform-diameter cylinder whose other end was driven by the rotating spindle of the milling machine.

There were a total of six mass transfer elements. Each of the upper five elements was ring-like in form and consisted of an aluminum substrate on which a layer of solid naphthalene was cast. These elements increased in axial length in the direction away from the free end. The lowermost element served as a lower end cap which held the assembled elements in place. The naphthalene coating at the cylindrical surface of the lower element was cast in place. On the other hand, the coating at the end face of the element was accomplished by condensing naphthalene vapor in conjunction with a subsequent smoothing procedure, leaving a film about 0.01 cm thick.

The lower end of the Delrin shaft was reduced in diameter to accommodate the mass transfer elements, and the step caused by the diameter reduction served as a positive stop for the assembly. Delrin (a free-machining plastic) was chosen as the shaft material to thermally isolate the mass transfer elements from the spindle of the milling machine.

The outer diameter D of the assembled rotating cylinder was 3.647 cm, while the reduced diameter of the lower portion of the Delrin shaft was 2.540 cm. The axial lengths of the lower three mass transfer elements were common and equal to 0.953 cm, the length of the fourth element was 1.588 cm, while the upper two elements were each 2.540 cm long. Overall, the length of the uniform diameter portion of the assembled cylinder was about 19.4 cm. All axial distances were measured from the free end of the cylinder by the coordinate x.

Figure 2 illustrates the presence of a thermocouple (TC), whose junction was positioned at the surface of the reduced diameter portion of the Delrin shaft, near its lower end. The lead wires were drawn through the cylinder assembly and terminated in the socket portion of a subminiature, quick-connect, connector taped to the side of the steel coupling. During periods of rotation, the thermocouple circuit was not closed. To accomplish the temperature measurement, the milling machine was braked to an abrupt halt and the plug portion of the connector mated with the socket portion. These operations, including the reading of the thermocouple e.m.f., were completed in 10 s. The thermocouple was made from calibrated 30-gage, chromel and constantan wire.

For these experiments, the milling machine was operated at rotational speeds between 260 and 2240 r.p.m., as measured by a solid-state digital tachometer.

Each data run was preceded by the preparation of the naphthalene surfaces. Then, the test elements, housed in airtight containers to suppress sublimation, were placed in the laboratory to attain thermal equilibrium. Subsequently, the individual elements were weighed and immediately inserted in proper order into the bore of a closed-bottomed Delrin tube, in which they fitted snugly. The tube and its contents of mass transfer elements were then mated with the Delrin shaft, and the assembly (including the tube) was fixed in place.

Rotation was then initiated, but no mass transfer occurred because of the presence of the Delrin tube. During this period, the rotating cylinder attained thermal equilibrium with its surroundings, and the approach to equilibrium was monitored by means of periodic readings of the cylinder thermocouple. When steady state was achieved, the protective tube was removed, thereby initiating the data run proper.

The duration of the run was selected to limit the sublimation-related recession to 0.0025 cm. During the run, the cylinder temperature was measured periodically. To terminate the run, the rotation was deactivated and the protective tube placed over the mass transfer elements. The individual elements were then weighed.

The mass transfer measurements were made with a solid-state analytical balance having a resolution of 0.00001 g. The measured changes of mass between the beginning and the end of a run ranged from 0.02 to 0.07 g, depending on the individual element.

RESULTS AND DISCUSSION

Data reduction

The measured change of mass and the duration of the data run yielded the rate of mass transfer $\dot{M}$ at each element. Then, the per-element mass transfer coefficient was evaluated from

$$K = (\dot{M}/A)/(\rho_{nw} - \rho_{n\infty}) \tag{4}$$

where A is the surface area of the element. The naphthalene vapor density ρ_{nw} at the subliming surface was determined by first computing the naphthalene vapor pressure from the vapor pressure–temperature relation [8] and then using the perfect gas law. The vapor density $\rho_{n\infty}$ in the surroundings was zero.

The per-element Sherwood number then followed as

$$Sh = KD/\mathscr{D}. \tag{5}$$

The diffusion coefficient $\mathscr{D}$ was eliminated via the Schmidt number $Sc = \nu/\mathscr{D}$, where $Sc = 2.5$ [8] and ν is the kinematic viscosity of air. The Reynolds number used to parameterize the data is that of equations (1) and (2).

Sherwood number results

The per-element Sherwood numbers are presented in Fig. 3 as a function of the dimensionless axial distance x/D measured from the free end of the rotating cylinder. In the figure, the Sherwood number for each element is plotted at the axial midpoint of the element. The respective axial distributions

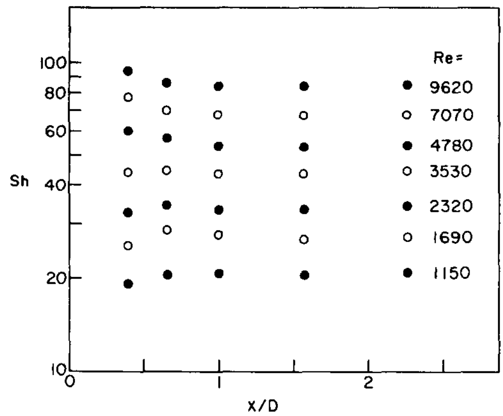

FIG. 3. Sherwood number distributions at the end-adjacent portion of the cylindrical surface of a rotating cylinder.

of the Sherwood number are parameterized by the Reynolds number, which ranges from 1150 to 9620 in seven steps.

Inspection of the figure reveals that over the range of x/D for which data are plotted, the axial variations of the Sherwood number are moderate, not exceeding 15%. Furthermore, as will be elaborated shortly, the axial variations attributable to the presence of the free end do not persist beyond $x/D = 1$. Therefore, the portion of the cylinder characterized by $x/D > 1$ can be regarded as being uninfluenced by end effects.

Further examination of Fig. 3 indicates a different pattern in the axial variations of the Sherwood number for the lower and higher Reynolds numbers. For the former, *Sh* increases at first, attains a maximum, and then diminishes slightly to the end-effect-free value. On the other hand, for the latter, *Sh* decreases monotonically to the end-effect-free value. To rationalize these different behaviors, it is relevant to discuss the end-effect-related processes which influence the Sherwood number on the cylindrical surface.

Relative to the surroundings, the free end of a rotating cylinder is at a reduced pressure. This pressure difference induces a flow from the surroundings toward the free end of the cylinder. In itself, such a flow would give rise to higher rates of mass transfer in the near-end region of the cylinder compared to that far from the end.

Acting to counteract the aforementioned effect is the influence of the mass transfer at the end face of the rotating cylinder. The naphthalene vapor which sublimes from the end face is convected radially outward across the face. Because of the induced surroundings-to-cylinder inflow discussed in the preceding paragraph, the naphthalene-enriched air from the end face may be swept over the end-adjacent portion of the cylinder. This would give rise to lower rates of mass transfer in the end-adjacent region than at locations well removed from the end.

The processes described in each of the preceding two paragraphs are in conflict. Not unexpectedly, the first of the processes dominates at higher Reynolds numbers, as witnessed by the relatively high end-adjacent values of *Sh* in evidence in Fig. 3. The figure also shows that the second process wins out at the lower Reynolds numbers. At $Re \sim 3500$, there appears to be a balance between the processes, since *Sh* is virtually independent of x/D.

Another noteworthy feature of Fig. 3 is that for all *Re*, the *Sh* value at the largest x/D is slightly greater (by 1.5–3%) than that at the adjacent x/D. This trend is as it should be for the present apparatus. The uppermost mass transfer element is situated adjacent to a nonsubliming surface (the Delrin shaft) at its upper end. The concentration of naphthalene vapor at the nonsubliming surface is zero, and this causes an upward axial diffusion of vapor from the boundary layer which envelops the upper portion of the uppermost element. It is this upward axial outflow of vapor which gives rise to the higher Sherwood numbers at the uppermost element.

It may also be noted that Sherwood numbers for the lowermost mass transfer element are not presented in Fig. 3. This is because the mass transfer rate at the cylindrical surface of the element could not be measured separately from the mass transfer rate at the end face.

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