HEAT AND MASS TRANSFER FROM A SHROUDED ROTATING DISK

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Introduction

To analyse the problems of the heat transfer from an axisymmetrical rotating body is very significant in extensive technological field; mechanical, chemical engineering and industrial. On the fundamental analysis, so many number of reports of experimental and theoretical studies on a rotating cylinder, disk, cone and sphere have been published. While, in industrial practice, these bodies are not rotating barely in open air as a single body, but they are usually rotating in casing or combined with other body in sophisticated configuration. On this standpoint, in this article, the authors report the experimental results on the case of a rotating disk which is confronting with a stationary disk as a fundamental treating of the problem in which the boundary condition of rotating boby is prescribed.

J. W. Mitchell *et al.*[1] reported the heat and mass transfer from a rotating disk shrouded with casing as a model of turbine wheel. J. W. Daily *et al.*[2], L. A. Maroti *et al.*[3], S. L. Soo[4], L. A. Dorfman[5] and G. L. Mellor *et al.*[8] analysed the pressure and velocity distributions around a rotating disk in a closed space. Regarding the effect of shroud, F. Kreith *et al.*[6] related that Sh_m of a naphthalene rotating disk can be expressed in a polynomials of c/d_0, $Re_m = m/2\pi\mu c$ and Re_r for the region of turbulent regime of $Re_r < 4\times10^5$. Dr. Kreith[7] also reported the heat and mass transfer from two co-rotating disks. Recently, G. L. Mellor *et al.*[8] obtained the velocity distribution between two disks.

There are essentially differences in air current characteristics around the rotating disk between with and without a shroud. As Daily and others related, there is a descending swirl on the rotating disk near its center, it is caused by the negative pressure due to the centrifugal force and there is also a centripetal flow under the surface of the stationary disk. It is considered that the shroud restricts the descending swirl, so that the centripetal flow compensates it and then the swirl is converted into the outward flow. As Kreith *et al.* stated, when c/d_0 decreases, Sh_m tends to decrease. But this tendency is not always recognized and is not grasped thoroughly.

In this paper, the authors studied the characteristics of heat and mass transfer with changing space gap between two disks and the effects of the dimension of the shroud experimentally, and observed the flow around the rotating disk.

The authors also investigated the effects of the shape of the stationary disk edge which might influence upon the chararcteristics of flow.

The Experimental Apparatus aud Procedure

Figure 1 shows a schematic arrangement of the experimental apparatus. A naphthalene layer 1 is cast in an aluminium sauser 2. The naphthalene disk has a diameter $d_0=2r_0=90$ mm and is electrically heated by Ni-Cr wire 3 under the saucer 2. The saucer 2 is bound on an aluminium disk 5 with a bakelite plate of 10 mm thick. Heating of Ni-Cr wire 6 in the disk 5 is adjusted so that the temperatures of the saucer 2 and the disk 5 are kept the same. The temperatures of the surface of naphthalene disk are measured by the thermocouples 7 of 0.3 mm diameter copper-constantan wires buried in the naphthalene disk.

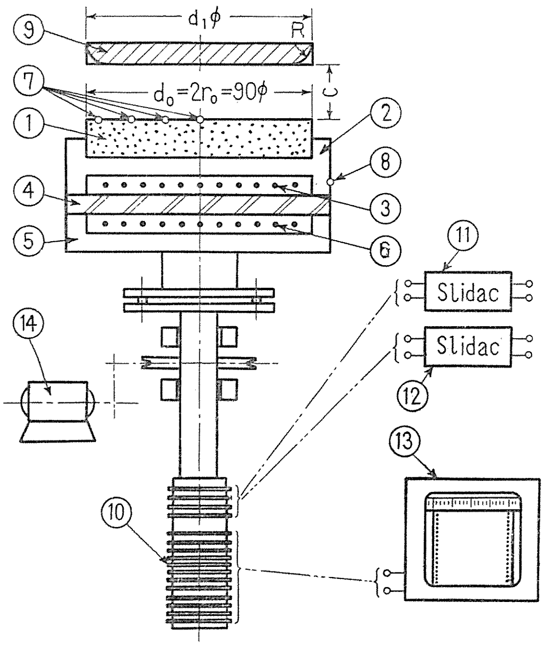

FIG. 1. An experimental apparatus.

The thermocouples 7 are placed about 1.0 mm beneath the surface of naphthalene so that the couples are not exposed above the surface during the experiment. Another thermocouples 8 are buried in the side of the saucer to calibrate the loss of heat flow. Both couples 7 and 8 are connected to an automatic temperature recorder through slip rings 10 which are fixed at the lower part of the rotating shaft. Thus the temperatures are recorded.

The surface temperature of the rotating disk is estimated by measuring the temperature gradient of naphthalene.

In this experiment is used an automatic temperature recorder with 6 measuring points with an accuracy of 0.3°C in the range of 0~5 mV of EMF. While the experiment is carried on, electric current through Ni-Cr heater is adjusted by a slidac 11 to maintain the temperature of the naphthalene surface constant, so that the sublimation of naphthalene may be kept at a constant rate of mass transfer. The lower heater 6 is also adjusted by a slidac 12 to keep the temperature 2 and 5 equal. The stationary disks 9 are made of polished polycarbonate resin in the diameter of $d_1=180$, 90, 60, 40 and 20 mm. The stationary disk is placed co-axially and parallel to the rotating disk with a gap c.

The gaps between the stationary and rotating disks are tested at $c=90$, 30, 20, 10, 7, 5, 3, 2 and 1 mm. Mean surface temperature of the rotating disk is:

$$\theta_{sm}=\frac{\int_s \theta dA}{\int_s dA}$$

where θ_{sm}: mean surface temperature of the rotating disk in °C
dA: elemental area of the surface of the rotating disk in m^2

Average heat transfer coefficient and average Nusselt number are obtained by the following equations

$$\alpha_m=\frac{0.86\,VI-q_r-q_s}{A_0(\theta_{sm}-\theta_\infty)} \quad (1) \qquad \mathrm{Nu_m}=\frac{\alpha_m \cdot r_0}{\lambda} \quad (2)$$

where α_m: average heat transfer coefficient, kcal/m²h°C
$\mathrm{Nu_m}$: average Nusselt number
A_0: surface area of the rotating disk, m^2
θ_∞: room temperature, °C
λ: thermal conductivity of ambient air at $\frac{\theta_{sm}+\theta_\infty}{2}$, kcal/mh°C
V, I: electric voltage and current loaded on heater 3, volt and amp. respectively
q_s: heat loss due to convection from the rotating disk except the surface area of naphthalene, kcal/h which is calculated with Izumi's result[9]
q_r: heat loss due to radiation from the whole surface of the rotating disk, kcal/h

$$q_r=4.88\cdot\varepsilon\cdot A_s\left\{\left(\frac{T_W}{100}\right)^4-\left(\frac{T_\infty}{100}\right)^4\right\} \quad (3)$$

where ε: emissivity by radiation
$\varepsilon=0.05$ for the aluminium surface[10]
$\varepsilon=0.85$ for naphthalene[11]
T_W: absolute surface temperature in Kelvin degree, °K
T_∞: absolute room temperature, °K
A_s: surface area, m^2

The sublimated loss of naphthalene is measured by a dial indicator with accuracy of 1/250 mm and calculated as a mathematical mean of depths of naphthalene lost on 4 radii.

In regard to mass transfer, average mass transfer coefficient K_{cm} and average Sherwood number $\mathrm{Sh_m}$ are evaluated as follows:

$$K_{cm}=\frac{\overline{m}R_vT_{sm}}{p_{vs}A_0} \quad (4) \qquad \mathrm{Sh}_m=\frac{K_{cm}\cdot r_0}{D_v} \quad (5)$$

where $\overline{m}$: total mass transfer rate in each test, kg/h

R_v: ideal gas constant of naphthalene vapor; 6.615 kgm/kg°K

T_{sm}: mean absolute temperature of naphthalene surface, equal to $\theta_{sm}+$ 273.16°K

D_v: diffusivity of naphthalene vapor into air[12], m^2/h

p_{vs}: vapor pressure of naphthalene at temperature T_{sm}[13], kg/m^2

The sublimated loss of naphthalene surface is expressed by a local mass transfer coefficient K_c m/h as follows:

$$\left.\begin{aligned}
&\overline{m}=\gamma\cdot A\cdot d && \text{kg/h}\\
&K_c=\frac{R_v\cdot T_s}{p_{vs}\cdot A}\gamma\cdot A\cdot d=\frac{R_vT_s}{p_{vs}}\gamma\cdot d && \text{m/h}\\
&K_{cm}=\frac{\int K_c dA}{\int dA} && \text{m/h}
\end{aligned}\right\} \quad (6)$$

where γ: specific weight of naphthalene, kg/m^3

d: lost depth of naphthalene by sublimation, m/h

The rotating disk is driven by a variable speed motor 14 with varied revolution. The rotational Reynolds numbers with a reference length r_0 are calculated by the following equation:

$$\mathrm{Re}_r=\frac{v_\theta\cdot r_0}{\nu} \quad (7)$$

where v_θ: peripheral speed of the rotating disk, m/h

ν: kinematic viscosity of air, m^2/h

Experimental Results and Consideration

As the authors stated in the introduction of this paper, there is an essential difference in the behavior of air flow on the surface of the rotating disk between with and without a shroud.

Dr. Schlichting in his book "Boundary layer theory" described the flow on a rotating disk in open air and Soo and Daily reported the results quantitatively for this case.

The authors also observed the flows on the rotating disk with a confronting stationary disk visualizing by means of the fume of tetrachloride titanium. As Figure 2 shows, the flow under stationary disk moves toward the center, but just above the rotating disk, the flow moves away from the center inducing the centripetal flow under the stationary disk.

Some part of the centrifugal flow is induced again in the centripetal flow at the outer edge of the disk. This phenomenon is evident in the case of $d_1 \geqq d_0$. As the gap between the rotating and stationary disks decreases, this tendency

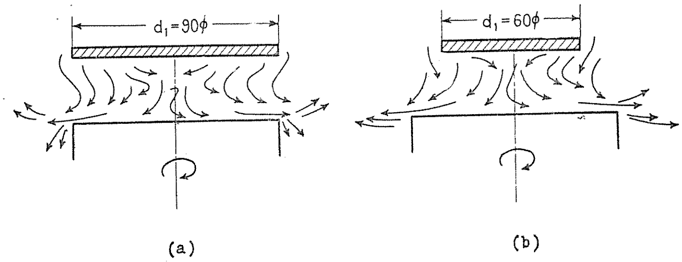

FIG. 2. Flow patterns around the rotating disk.

becomes very strong, and the centrifugal flow above the rotating disk is restricted by the centripetal flow.

In the case of gap being small, a disturbance occurs around the outer circumference of the stationary disk.

This means while the centripetal flow decreases the sublimation of naphthalene, at the outer edge of the stationary disk $r=d_1/2$, disturbance increases the sublimation. For $d_1 \geqq d_0$, the sublimation will decrease, because of a circulating flow and no disturbance The flow in the gap are three-dimensional, so it is difficult to find out the boundary layer condition in this region. In the case of $d_1<d_0$, for the region of $r \geqq d_1/2$, as the flow on the rotating disk are outward flow from the center, the state of sublimation in this region are the same as those in open air.

Figure 3 shows the relations of Sherwood number to the gap.

Taking the diameter of the stationary disk d_1 as a parameter at the revolution of the rotating disk of 400 rpm ($Re_r=5.4\times10^3$), Sherwood number is expressed as $Sh_m/Sh_{m\infty}$ versus gap ratio c/d_0. The values of $Sh_{m\infty}$ are reported in author's previous paper[14]. In this figure, $Sh_m/Sh_{m\infty}$ is seen as unity in the range of $c/d_0>0.22$ and this means that there is no effect of the stationary disk. In the region of $c/d_0<0.22$, the smaller the diameter of the stationary disk is, the wider becomes the range of c/d_0 where $Sh_m/Sh_{m\infty}$ remains unity. For $d_1=$ 20 mm, $Sh_m/Sh_{m\infty}$ is over unity in the range of $c/d_0>0.022$. In other word, the larger the diameter of the stationary disk is, the faster $Sh_m/Sh_{m\infty}$ falls when c/d_0 decreases from 0.22. For $d_1=60$, 40 and 20 mm, the minimum value of $Sh_m/Sh_{m\infty}$ can be observed at $c/d_0=0.022$.

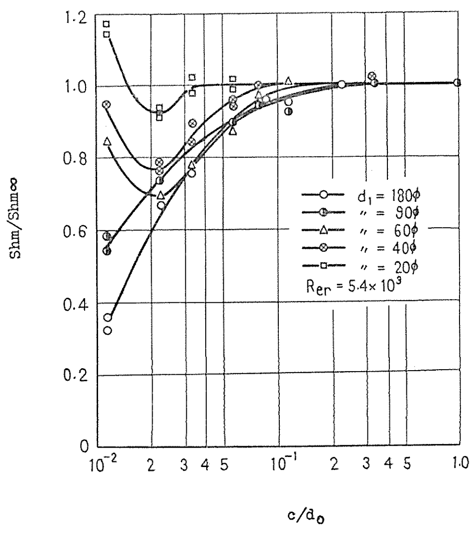

FIG. 3. Variations of Sh_m for various dimensions of the stationary disk to c/d_0.

These facts may be qualitatively explained by the flow state around the rotating disk as shown in Figure 2. For the same gap c, in the case of $d_1=180$ mm, it is

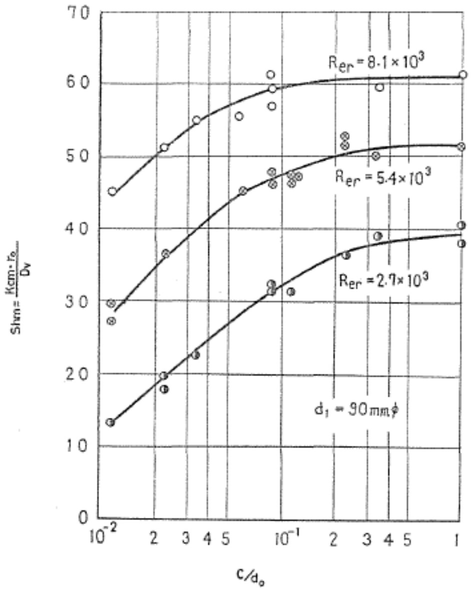

FIG. 4. The values of Sh_m versus c/d_0 at each Re_r for the stationary disk of 90 mm in diameter.

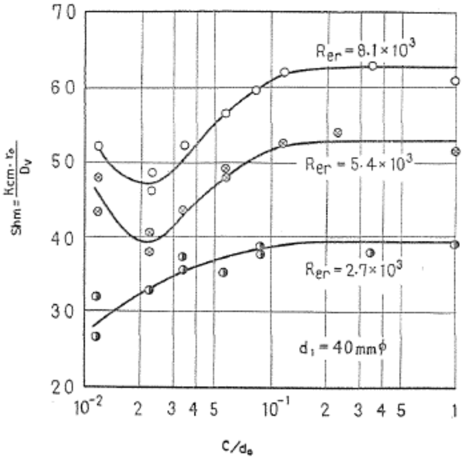

FIG. 5. The values of Sh_m versus c/d_0 at each Re_r for the stationary disk of 40 mm in diameter.

predicted that fresh air into gap is more restricted to induce than in the case of $d_1=90$ mm. Figures 4 and 5 show the relations of Sh_m to c/d_0 with Re_r as a parameter. Figure 4 is an example of this relation at $d_1=90$ mm, with several revolutions of the rotating disk. The curves have the same reducing tendency as c/d_0 decreases. The authors call this tendency the "pattern 1". The value of c/d_0 at which a decrease of the value of Sh_m begins is larger at lower revolution of the rotating disk than at higher one. The values of Sh_m at $c/d_0=1$ are the same as $Sh_{m\infty}$ which is Sherwood number in open air. Kreith *et al.* relate about the effect of the gap in their similar treatment, as at $Re_r<2.96\times10^4$, the value of Sh_m reduces with decrease of c/d_0, but at $Re_r>1.19\times10^5$ Sh_m takes a maximum value near $c/d_0\approx0.1$ and then again decreases as c/d_0 diminishes. In author's experiment, the same tendency is observed. The start point of reduction of Sh_m in case of $Re_r=8.1\times10^3$ locates near $c/d_0\approx0.1$, and in case of Re_r less than above value, c/d_0 at which reduction of Sh_m starts shifts to $c/d_0\approx0.1$.

Figure 5 shows the relation between Sh_m and c/d_0 in the case of $d_1=40$ mm ($d_1/d_0=0.45$). At $Re_r=5.4\times10^3$ ($n=400$ rpm), Sh_m is minimum at $c/d_0=0.022$, and as c/d_0 decreases more, Sh_m grows again. Authors call this tendency the "pattern 2". At $Re_r=2.7\times10^3$ ($n=200$ rpm) this tendency is not observed, it looks like the "pattern 1".

This means the pattern is affected not only by d_1/d_0 but also by the number of revolution of the rotating disk.

Figure 6 shows the state of the lost depth of naphthalene and the temperature on the surface of the rotating disk.

Figures 6 (a), (b), (c) and (d) show the state belonging to the "pattern 1" in which Sh_m reduces with the diminution of c/d_0. And Figures 6 (e), (f), (g)

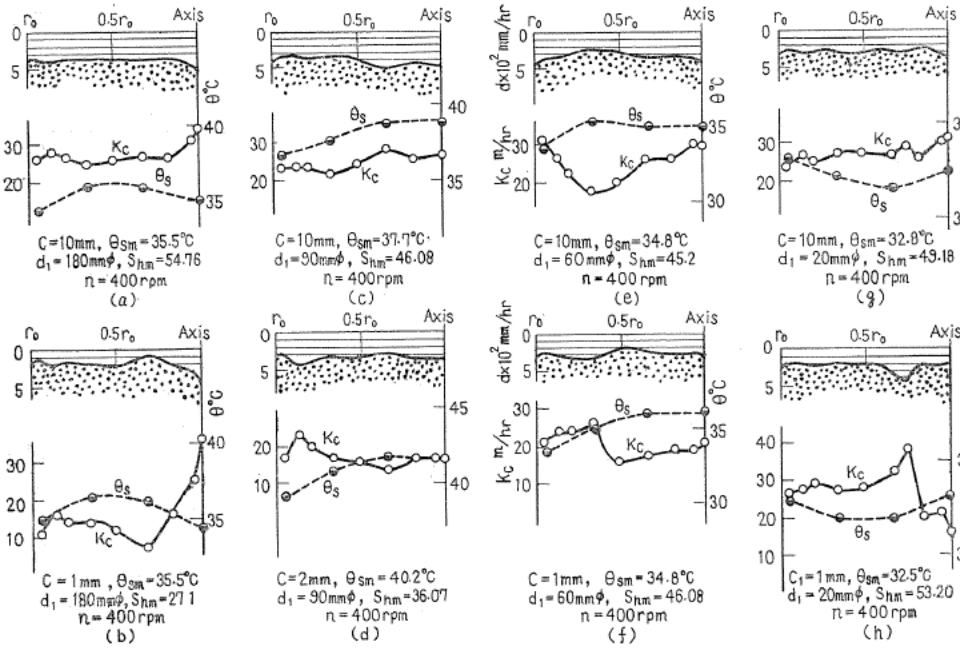

FIG. 6. K_c and the lost depth of naphthalene on the surface of the rotating disk, (a)~(d) belong to the "pattern 1", (e)~(h) belong to the "pattern 2".

and (h) show the tendency of the "pattern 2" which has the minimum value of Sh_m.

Reviewing Fig. 6 precisely, in the "pattern 2", Figs. (f) and (h), at $r=d_1/2$ which corresponds to the outer edge of the stationary disk, it is recognized that the lost depth of naphthalene d mm/h and K_c m/h has considerably large values.

But in Figs. (e) and (g) which belong to the case of large gap (c=10 mm), the above tendency is not recognized and Sh_m has nearly the same value as $Sh_{m\infty}$. The reasons for getting a maximum value of K_c at the outer edge of the stationary disk are that there is eddy caused by in- and outward-flow of air and that mass transfer occurs vigorously.

In outer region around the edge of the stationary disk, $r\geqq d_1/2$, K_c has approximately the same value as in mass transfer in open air. This means that at $r\geqq d_1/2$, air flows are not affected by the stationary disk, the state of flow is similar to that in open air. It is considered that at $r\leqq d_1/2$, the centrifugal flow and centripetal flow in the gap between two disks are retained on each other and a partially closed space is formed, thus diffusion of naphthalene is restricted, as p_v increases, $(p_{vs}-p_v)$ decreases and then K_c attains a small value. This is proved by the fact observed in this experiment that the surface temperature of naphthalene under the stationary disk, $r\leqq d_1/2$, is high.

Consequently, in the regions of $r\geqq d_1/2$ and $r\leqq d_1/2$ mass diffusion must be treated in different ways. In $r\leqq d_1/2$, the flows of air are regarded as those in the closed space, and the diffusivity is that in the stagnated space.

In $r\geqq d_1/2$, the flow and diffusivity are expressed nearly as those in open air. Contrary to the case of $d_1<d_0$, as stated above, in the case of $d_1\geqq d_0$, the variation

of K_c is relatively smooth, especially in the case of $d_1=d_0=90$ mm and $c=2$ mm, the outer edge of the rotating disk is the point of collision of in- and outward-flows of air to the gap, and a large value of K_c is observed at $r/r_0 \approx 0.93$.

In the case of (b), $d_1=180$ mm and $c=1$ mm, the value of K_c decreases as the radius of disk increases. This is considered due to the fact that the stationary disk is covered again with the air containing naphthalene vapor which has been thrown out from the rotating disk surface. And in this case, K_c is nearly 10～15 m/h and is equal to K_c in the case of (h). In the cases of (a) and (c), $c/d_0=0.11$ ($c=10$ mm), the value of K_c has no evident variation such as in the case of $c=1$ mm and is approximately equal to the confirmed value with the rotating disk in open air. When there is a considerably large gap between two disks, no disturbance of air flow and no stagnation of naphthalene vapor are observed.

In Fig. 5 for the case of $d_1<d_0$, the flow pattern is influenced by the revolution of the rotating disk and Figure 7 shows this more evidently. While in both cases of $d_1=40$ mm and 20 mm, and 200 rpm, the curves show the "pattern 1", others shown in Fig. 5 the "pattern 2". The critical number of revolution at which the "pattern 1" converts into the "pattern 2" depends upon the value of d_1 and it seems that the larger d_1 is, the lower the critical revolution becomes. The cause by which the "pattern 1" converts into the "pattern 2" seems as mentioned above, that is when c/d_0 is small, maximum value of K_c occurs near $r=d_1/2$.

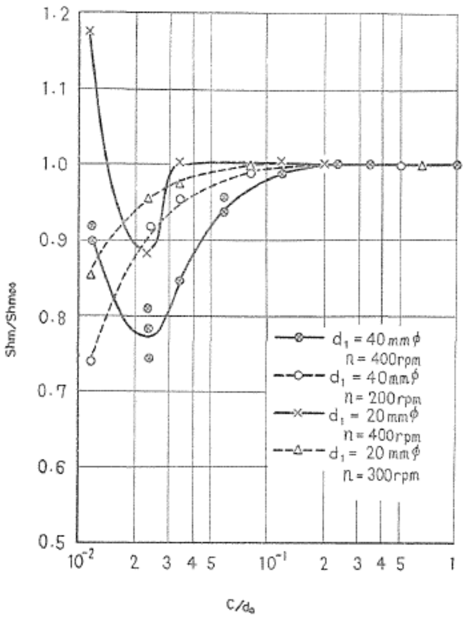

FIG. 7. Effects of Re_r on the pattern of the variation of Sh_m.

Moreover the influence of the revolution is not negligible either. As this example, Figure 8 shows that the lost depth of naphthalene on the rotating disk surface for $c=1$ mm, $d_1=40$ mm and at the revolutions $n=200$ and 400 rpm.

As seen in the case of (a), in the region of $r \geqq d_1/2$, the lost depth and K_c are almost the same as in open air, while in the region of $r \leqq d_1/2$ the lost depth is quite small.

It is considered that this phenomenon is caused by low depression of pressure and low velocity of air under the centrifugal force, and insufficient exhaust of naphthalene vapor from the gap. In the case of (b), the revolution is higher than in the case of (a) and it shows the "pattern 2". In the region of $r \leqq d_1/2$, the value of K_c is 8～15 m/h and is about twice as large as $K_c=4\sim7$ m/h in (a).

The value of K_{cm} in (b) is higher than in (a), and this fact is due to the effect of the number of revolutions.

Next, authors should describe about the influence of the shape of the stationary disk edge. In the case of the right-angled edge, inflow of air must be disturbed into an eddy. So, authors gave some roundness to the lower side of the stationary disk edge and studied the effect of this roundness. Figure 9 shows these effects

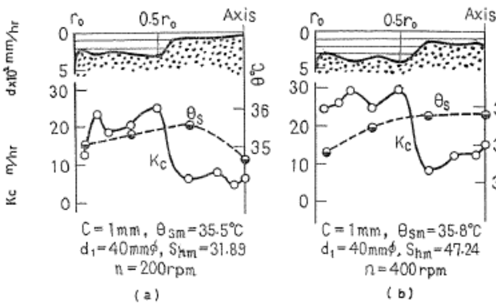

FIG. 8. K_c and the state of the surface after sublimation of naphthalene as to FIG. 7.

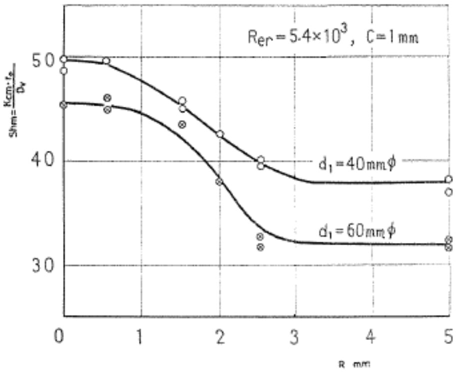

FIG. 9. Effect of the roundness of the stationary disk edge on Sh_m.

at various sizes of roundness such as $R=0.5$, 1.5, 2.0, 2.5 and 5.0 mm in the case of $n=400$ rpm, $c=1$ mm and $c/d_0=0.011$, where $R=0$ means the right-angled edge. As Figure 9 shows, in both cases of $d_1=40$ mm and $d_1=60$ mm, changing from $R=0$ to $R=5$, Sh_m decreases rapidly until it reaches the point of $R=2.5$ and then it becomes flat. The reduction of Sh_m remarkable in the range of $R=1.5\sim2.5$. The effect of round off of the under edge of the stationary disk on the lost depth of naphthalene is shown in Figs. 10 (a) and (b).

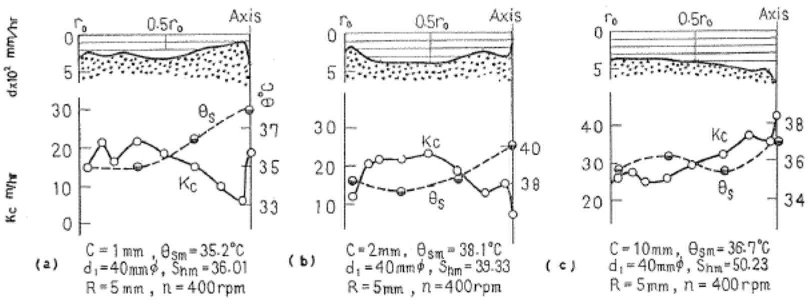

FIG. 10. Effect of the roundness of the stationary disk edge on K_c and the lost depth of naphthalene.

At the radius corresponding to the stationary disk edge, a notable lost depth could not be observed. The lost depth under the stationary disk and the value of K_c show tendency of gradual decrease in $r\leqq d_1/2$. In $r\geqq d_1/2$ the value of K_c is approximately equal to K_c in open air. The case of $R=0$ should be referred to Fig. 8 (b). For $c=10$ mm ($c/d_0=0.11$), the inflow of air under the stationary disk is more fluent and as mentioned in authors' previous report a large mass transfer is observed at the center just like that from the rotating disk in open air. Figure 11 shows the effect of the round off of the stationary disk edge on the curves of $Sh_m/Sh_{m\infty}$ versus c/d_0 in the case of $d_1=40$ mm, $Re_r=5.4\times10^3$ and $R=5$ mm. Authors plotted the curve of the case of $R=0$ for reference. In the curve of $R=5$ mm, when c/d_0 decreases, $Sh_m/Sh_{m\infty}$ starts to reduce at $c/d_0\approx0.33$

and continues its reduction. A rise is not observed at $c/d_0=0.011$.

It is explained by the fact that the disturbance due to interference of the centrifugal and centripetal flows between two disks or eddy which is produced by the stationary disk edge is reduced or diminishes by this round off, so that there is no growth in mass transfer. Comparing the curves of $R=0$ with $R=5$ mm, in the range of $0.022 \leqq c/d_0 \leqq 0.22$ the lost depths are not equal. For $R=0$, Sh_m has the minimum value of 38.4 at $c/d_0=0.022$ and for $R=5$ mm, Sh_m takes 42.1 and shows larger values than that for $R=0$. These differences can be explained as follows; For $R=0$, at $c/d_0 \approx 0.022$, there is a slight inflow of air under the stationary disk and the diffusion is restricted and mass flow is weak over the entire area of the rotating disk surface. For $R=5$ mm, the inflow resistance at the stationary disk edge is less than for $R=0$, so that large quantity of inflow of air makes active diffusion and mass transfer on the whole. Similar relations between heat and mass transfer in both patterns are shown in Figs. 12 and 13. Average mass transfer coefficient K_{cm} and average heat transfer coefficient α_m which are calculated with the values of Sh_m and Nu_m, have a relation of similarity. And the ratio of K_{cm}/α_m is equal to 1.35.

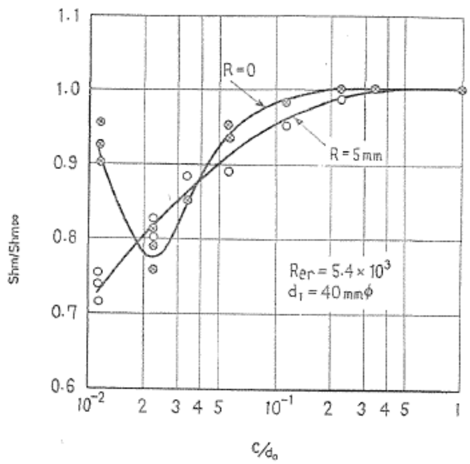

FIG. 11. Comparison of Sh_m for the stationary disk edge with and without roundness.

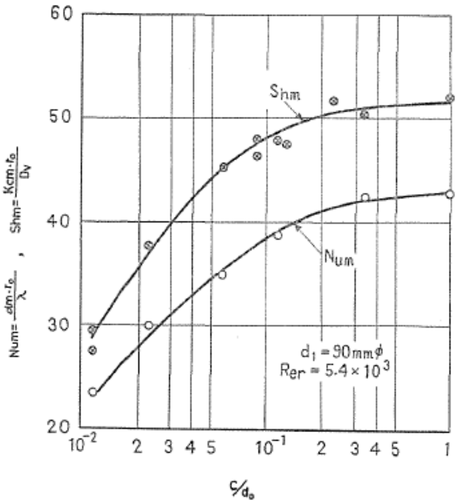

FIG. 12. Analogy between heat and mass transfers for the "pattern 1".

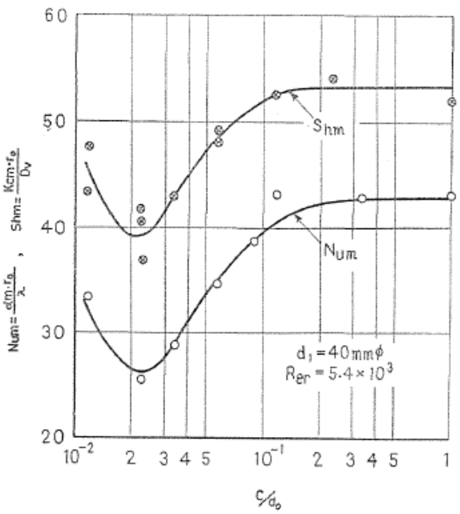

FIG. 13. Analogy between heat and mass transfers for the "pattern 2".

This value coincides with the result which the authors have reported in the previous paper on an experiment with naphthalene disk rotating in a cylinder and in open air. Now, let us consider Colburn's j-factor in the terms of Re_r calculated with the peripheral speed of the rotating disk.

j_H and j_D, factors of heat and mass transfer are expressed as follows:

$$\left.\begin{aligned} j_H &= \frac{Nu_m}{Re_r \cdot Pr} \cdot (Pr)^{2/3} \\ j_D &= \frac{Sh_m}{Re_r \cdot Sc} \cdot (Sc)^{2/3} \end{aligned}\right\} \tag{7}$$

In Figs. 12 and 13, at $c/d_0=0.055$, $Nu_m=34$ and $Sh_m=45.5$ and 48, the following are given for $Pr=0.72$ and $Sc=2.58$

$$j_H = \frac{34}{5.4\times10^3\times0.72}\times(0.72)^{2/3} = 7.00\times10^{-3}$$

$$j_D = \frac{45.5}{5.4\times10^3\times2.58}\times(2.58)^{2/3} = 6.13\times10^{-3}$$

$$j_D = \frac{48}{5.4\times10^3\times2.58}\times(2.58)^{2/3} = 6.47\times10^{-3}$$

The difference between j_H and j_D is 12.5% of the value of j_H.

The maximum difference for each value of c/d_0 is 16.9%, so it may be considered that $j_H \approx j_D$, hence the similarity between heat and mass transfer is proved.

Conclusions

Through the experiment on heat and mass transfer from a naphthalene rotating disk with a confronting stationary disk having a gap c, the authors come to the conclusions as follows:

(1) Changing the gap between two disks, the state of the variation of mass transfer is classified into two patterns: in the case of $d_1>d_0$, with decrease of c/d_0 heat and mass transfer continuously reduce. On the other hand, in the case of $d_1<d_0$, with the decrease of c/d_0, heat and mass transfer reduce, but at $c/d_0=0.011$, they grow again.

(2) This growth of K_c is due to much sublimation caused by eddy at $r=d_1/2$ (Figs. 6 (f) and (h)).

(3) Eddy and disturbance in air flow are caused by the shape of the stationary disk edge at $r=d_1/2$. This is proved by the fact that round off the edge of the stationary disk facing the rotating disk suppresses the growth of K_c (Fig. 10).

(4) The effect of the stationary disk disappears in $c/d_0>0.33$, and in this region, Sh_m is equal to that in open air (Figs. 3, 4, 5 and 7).

(5) The lost depth of naphthalene surface is not uniform and it differs in the region of $r\leqq d_1/2$ and in that of $r\geqq d_1/2$. When two disks are very close to each other, the difference is remarkable (Figs. 6, 8 and 10).

(6) Similarity between heat and mass transfer is confirmed by the investigation on j-factor. K_{cm}/α_m is estimated to be 1.35 and is equal to the result in the case of a disk rotating in open air and in a cylinder (Figs. 12 and 13).

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