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HEAT TRANSFER BY THE INDUCED FLOW ABOUT A ROTATING CONE OF NON-UNIFORM SURFACE TEMPERATURE*

C. L. TIEN†
University of California, Berkeley

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Abstract—The present paper is concerned with the heat-transfer characteristics by the induced flow, laminar or turbulent, about a rotating cone with non-uniform surface-temperature distributions. Consideration is first given to the theoretical calculation based on various existing theories. Discussed in details are the two cases: the power-law and the step-change surface-temperature distributions. The case of step-change distribution is further studied experimentally through the naphthalene-sublimation technique. The step-change surface temperature is simulated by a step-change surface sublimation. Measurements of the sublimation rate from rotating cones of various vertex angles are made in both the laminar and turbulent flow regions. They are then compared with the predicted mass-transfer results obtained from the analytically established heat-transfer relation through the heat and mass-transfer analogy argument.

NOMENCLATURE

a, radius of thermally insulated or impermeable surface [ft];
A, heat or mass-transfer area [ft²];
b_1, dimensionless constant defined in equation (4);
b_2, dimensionless constant in the eddy-diffusivity profile [7], $b_2 = 0{\cdot}0075$;
B, dimensionless constant defined in equation (5);
D_v, mass diffusivity of naphthalene vapor in air [ft²/s];
$\bar{h}$, average heat-transfer coefficient [Btu/s ft² degF];
h_x, local heat-transfer coefficient [Btu/s ft² degF];
k, thermal conductivity [Btu/s ft degF];
$\bar{k}_c$, average mass-transfer coefficient [lbm/ft³];
K_1, dimensionless constant defined in equation (2);
K_2, dimensionless constant defined in equation (10);
m, dimensionless constant defined in equation (5);
m_v, rate of mass transfer [lbm/s];
Nu_x, local Nusselt number at x;
$\overline{Nu}$, average Nusselt number;
p_{vw}, partial pressure of naphthalene vapor at T_w [lb/ft²];
Pr, Prandtl number;
q, local heat flux [Btu/s ft²];
R_v, gas constant for naphthalene vapor [ft lb/lbm degR];
Re_0, rotational Reynolds number evaluated at x_0;
Re_x, rotational Reynolds number defined in (14);
s_1, dimensionless constant defined in equation (3);
s_2, dimensionless constant defined in equation (11);
Sc, Schmidt number;
$\overline{Sh}$, average Sherwood number defined in equation (16);
t_1, dimensionless constant defined in equation (4);
t_2, dimensionless constant in the eddy-diffusivity profile [7], $t_2 = 0{\cdot}54$;
T, temperature [°F];

* Since the completion of the present paper a number of closely related works have become available [16, 17, 18]. They will be mentioned only briefly in the paper.
† Associate Professor of Mechanical Engineering.

T_w, wall temperature [°F];
T_∞, freestream temperature [°F];
T_0, temperature defined in equation (7) [°F];
u, radial velocity component [ft/s];
x, radial coordinate [ft];
x_0, slant height of the cone [ft];
X, integration variable in equations (1) and (9) [ft^{s_1}];
z, coordinate normal to the surface [ft].

Greek symbols
α, half vertex angle of the cone [deg];
Γ, gamma function;
λ, dimensionless ratio (a/x);
λ_0, dimensionless ratio (a/x_0);
μ_1, dimensionless constant in equation (3);
μ_2, dimensionless constant in equation (11);
ν, kinematic viscosity [ft²/s];
ω, rotational speed [rad/s].

INTRODUCTION

THE PROBLEM dealing with heat transfer by flow around rotating disks (i.e. cones of 180° vertex angle) and cones has received considerable attention in recent years, partly because of its importance in practical applications but also due to its being a simple ideal model for theoretical and experimental investigations of three-dimensional boundary-layer characteristics. Extensive theoretical investigations have been made on the laminar heat transfer [1, 2, 3, 4] and some semi-empirical and approximate theories have been developed to explain the turbulent heat-transfer characteristics [5, 6, 7]. A number of investigators [5, 6, 8, 9] have also carried out experimental studies for both laminar and turbulent cases, and have obtained results in good agreement with prediction. In most existing theoretical and experimental works, however, results were obtained for the case of uniform surface temperature. A few works [2, 7, 10, 11, 12]* of theoretical nature have been concerned with non-isothermal disks and cones, but no experimental studies have ever been reported for those cases.

The present paper is concerned with the heat-transfer characteristics by the induced flow about a rotating cone of non-uniform surface-temperature distribution. Heat transfer in both laminar and turbulent flow regimes are under investigation. Consideration is first given to the theoretical calculations based on various existing theories, which include the similarity solution of Hartnett [11, 12], the approximate solution by use of Lighthill technique [13] and the modified Lighthill theory by Davies [7, 10]. Two cases are discussed: the power-law and the step-change surface-temperature distributions. In the experimental study, only the case of step-change distribution will be examined because of its simple experimentation. The experimental model is a naphthalene-coated surface, from which the rates of sublimation are measured [6, 8]. The rate of mass injection due to sublimation is so low that the process is equivalent to the heat-transfer process from an impervious surface. The step-change surface temperature is simulated by a step-change surface sublimation from no sublimation to sublimation. Measurements from cones of various vertex angles are made in both the laminar and the turbulent flow regions, and are compared with the predicted results.

THEORETICAL CONSIDERATIONS

The only existing solution concerned with heat transfer by the induced flow from non-isothermal rotating cones is that given by Hartnett [11, 12] for laminar heat transfer from rotating cones of power-law surface-temperature distribution. The solution is an exact one for the non-dissipative laminar boundary layer and the restriction on the power-law temperature distribution arises from similarity consideration. There exists no similarity solution for other surface-temperature distributions. An approximate solution for any kind of surface-temperature distribution can be obtained through the Lighthill technique [13] which employs a linear velocity profile in the boundary layer and applies the von Mises transformation to the energy equation. The linear velocity profile, strictly speaking, is a valid approximation only for the case of large Prandtl numbers, although relatively good agreement with exact solution has been demonstrated by Lighthill for a flat plate of uniform surface temperature in the moderate range of Prandtl numbers, i.e. Prandtl numbers of order of one.

* See also recent works [16, 17, 18].

The use of the Lighthill technique to the rotating-disk problem was first suggested and modified by Davies [7, 10], by employing a power-law velocity profile. For the induced-flow case the approximate solution of Davies can be readily extended to the rotating-cone problem by the transformation suggested by Wu [14] and Tien [3]. The approximate solution is of considerable importance as a result of its applicability to any surface-temperature condition, however, its accuracy should first be assessed by comparing with exact solutions and experimental measurements.

In the laminar, incompressible case, the approximate solution of Davies [10] can be easily modified to give the local heat flux at a radial position x on the cone surface as:

$$q(x) = K_1 k \left(\frac{\omega \sin \alpha}{\nu}\right)^{1/2} (Pr)^{1/(2+t_1)} x^{-1} \frac{d}{dx} \int_0^{x^{s_1}} (x^{s_1} - X)^{\mu_1 - 1} [T_w(X) - T_\infty] \, dX \quad (1)$$

where $K_1 = \pi^{-1} (2)^{-\mu_1} (1 + t_1)^{\mu_1} (2 + t_1)^{\mu_1 - 1} \Gamma(\mu_1) (\sin \mu_1 \pi) k \times b_1^{1-\mu_1}$ (2)

$$s_1 = \frac{2(2 + t_1)}{(1 + t_1)}, \; \mu_1 = \frac{2}{s_1} \quad (3)$$

and b_1 and t_1 are related to the radial-component velocity u by

$$u = (\omega x \sin \alpha) \, b_1 \left[z \left(\frac{\omega \sin \alpha}{\nu} \right) \right]^{t_1} \quad (4)$$

Equation (4) is an approximate expression of the actual radial-velocity profile. The case of $t_1 = 1{\cdot}0$ and $b_1 = 0{\cdot}51$, which gives $K_1 = 0{\cdot}207$ and $s_1 = 3{\cdot}0$, corresponds to the approximation of the linear velocity profile first suggested by Lighthill in the analysis of heat transfer for boundary layers over a flat plate. A better fit to the exact solution of velocity profile was suggested by Davies by letting $t_1 = 0{\cdot}67$ and $b_1 = 0{\cdot}245$, and consequently, $K_1 = 0{\cdot}159$ and $s_1 = 3{\cdot}20$.

For a power-law surface-temperature distribution

$$T_w - T_\infty = B x^m \quad (5)$$

the approximate solution in terms of the local Nusselt number can be obtained from (1) as:

$$Nu_x \equiv \frac{h_x}{k} \left(\frac{\nu}{\omega \sin \alpha} \right)^{1/2} = K_1 (m + 2) \frac{\Gamma[(m + s_1)/s_1] \, \Gamma(\mu_1)}{\Gamma[(m + s_1 + 2)/s_1]} \times Pr^{1/(2+t_1)} \quad (6)$$

Shown in Table 1 is the comparison with the exact solution of heat transfer for a power-law

Table 1. Comparison between exact and approximate solutions of laminar heat transfer from rotating cones of power-law surface-temperature distributions

Pr	m	Nu_x (Exact [12])	Nu_x (6) ($t_1 = 0{\cdot}67$)	Nu_x (6) ($t_1 = 1{\cdot}0$)
1·0	0	0·396	0·509	0·620
1·0	4	0·769	0·869	1·001
1·0	10	1·073	1·161	1·296
10	0	1·13	1·21	1·33
10	4	1·95	2·06	2·15
10	10	2·60	2·75	2·79
100	0	2·69	2·85	2·88
100	4	4·46	4·87	4·65
100	10	5·95	6·50	6·02

surface-temperature distribution obtained numerically by Hartnett [12]. In general, the approximate solution based on a power-law velocity profile gives a reasonably good agreement with the exact solution in the range of moderate and high Prandtl numbers. At Prandtl numbers of order of 100 or larger, however, the linear velocity profile does give better results than the power-law velocity profile.

In practical applications, a step-change surface temperature is probably more common than the power-law one, but theoretically, there is no exact solution in this case. For a step-change surface temperature such as

$$T_w = T_\infty \text{ for } x < a, \; T_w = T_0 \text{ for } x \geqslant a \quad (7)$$

the approximate method as given in (1) yields the following expression for the local Nusselt number:

$$Nu_x = K_1 s_1 (1 - \lambda^{s_1})^{(\mu_1 - 1)} Pr^{1/(2-t_1)} \quad (8)$$

and $\lambda = (a/x)$. The accuracy of the above solution will be discussed when the analogous expression of mass transfer is compared with the mass-transfer measurements. An approximate solution for $Pr = 0{\cdot}72$ from integral method has been recently reported by Schnurr [18].

For turbulent flows over rotating disks or cones, all existing heat-transfer calculations are of approximate nature. The friction-analogy calculation [5, 6], which has been quite successful in correlating with the experimental data from surfaces of uniform temperature, cannot be easily extended to take into account the effect of non-uniform surface temperature. Based on the same mathematical technique as in the laminar case, Davies [7] has given an approximate solution for the limiting case when the disk surface is entirely covered by turbulent flow. To achieve such a solution, however, he employed a number of assumptions, among which are the power-law radial-velocity and eddy-diffusivity profiles and equal eddy diffusivities for momentum and heat. For the case of uniform surface temperature, the approximate solution has been found in good agreement with experimental data [8]. The local heat flux at a radial position x is given as

$$q(x) = k \left(\frac{\omega \sin \alpha}{\nu}\right)^{4/5} Pr \left(\frac{K_2}{s_2 x}\right) \frac{\mathrm{d}}{\mathrm{d}x} \int_0^{x^{s_2}} (x^{s_2} - X)^{\mu_2 - 1} [T_w(X) - T_\infty] \, \mathrm{d}X \qquad (9)$$

where

$$K_2 = \pi^{-1} \left(\tfrac{13}{5}\right)^{\mu_2(1-t_2)} \mu_2^{-\mu_2} \Gamma(\mu_2) (\sin \mu_2 \pi) \, b_2^{\mu_2} \qquad (10)$$

$$s_2 = \tfrac{13}{5}(2 - t_2), \quad \mu_2 = \frac{1}{2 - t_2} \qquad (11)$$

and b_2 and t_2 are two matching constants in the power-law eddy-diffusivity profile and are given by Davies as 0·0075 and 0·54 respectively. For the above values of b_2 and t_2, there follow $K_2 = 0{\cdot}0215$, $s_2 = 3{\cdot}8$ and $\mu_2 = 0{\cdot}685$. The value of $K_2 = 0{\cdot}0253$ has been implicitly given by Davies [7] and used by Tien and Campbell [8] in their comparison with experimental data, however, a recaiculation shows $K_2 = 0{\cdot}0215$. It should also be noted that due to a misprint, the expressions of K_1 and K_2 in Davies paper [7] should be divided by π.

From (9), the local Nusselt number for a power-law surface-temperature distribution is

$$Nu_x = K_2 \left(\frac{s_2 \mu_2 + m}{s_2}\right) \frac{\Gamma[(m + s_2)/s_2] \, \Gamma(\mu_2)}{\Gamma[(m + s_2 + s_2 \mu_2)/s_2]} Pr \, Re_x^{0 \cdot 3} \qquad (12)$$

and for a step-change surface-temperature distribution it is

$$Nu_x = K_2 (1 - \lambda^{s_2})^{\mu_2 - 1} Pr \, Re_x^{0 \cdot 3} \qquad (13)$$

where the rotational Reynolds number is defined as

$$Re_x \equiv \frac{\omega x^2 \sin \alpha}{\nu} \qquad (14)$$

In the special case of uniform surface temperature ($m = 0$ or $\lambda = 0$), both equations reduce to $Nu_x = K_2 \, Pr \, Re_x^{0 \cdot 3}$. The results of the step-change case will be discussed with respect to the experimental measurements.

EXPERIMENTAL APPARATUS

The schematic of the experimental setup is shown in Fig. 1. The rate of sublimation from various conical surfaces rotating in air was measured in this experiment. The vertex angles

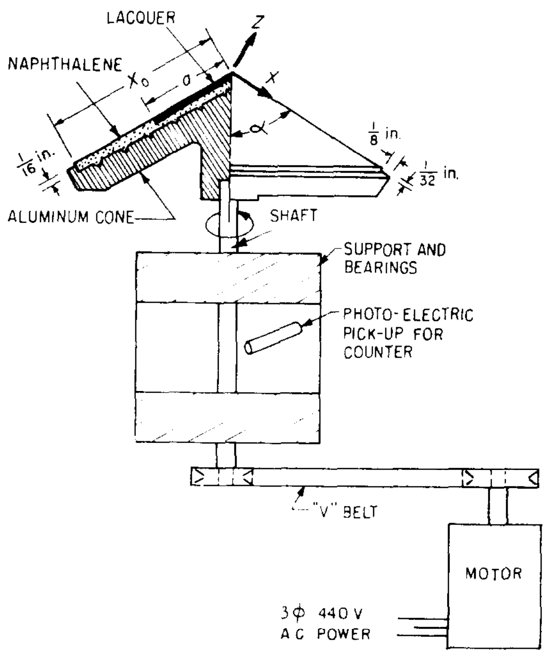

FIG. 1. Sketch of the experimental equipment.

of the cones investigated were 60°, 90°, 120°, 150° and 180° (disk). The cones were rotated at constant speeds ranging from 780 rev/min to 10000 rev/min, which correspond to a range of conditions from entirely laminar flow to that the outer 70 per cent of the surface area is covered by turbulent flow. For each run, the speed, the ambient temperature, time interval and mass loss due to sublimation were recorded. From the data obtained, the Sherwood number was calculated. Details of the experimental procedure and precautions follow closely those in the previous works [6, 8] and will not be repeated here.

The present experiment differs from the previous investigations [6, 8] in the use of non-uniform surface conditions. For a step-change surface-temperature distribution, the mass-transfer simulation is to have a conical surface of no sublimation in the central portion and sublimation in the outer zone. This was accomplished as follows: In the central portion of radius a of a naphthalene-coated cone, a cut of $\frac{1}{64}$ in. deep was taken and was filled by painting in thin layers of the Duco Lacquer (made by E. I. Du Pont De Nemours & Co., Inc., Wilmington, Delaware) till it became in level with the rest of the surface. The paint was left overnight to dry and then the whole surface was machined smooth for experiment. Experiments were performed for various cones at two values of λ_0, $\lambda_0 = a/x_0 = 0{\cdot}25$ and $0{\cdot}5$.

EXPERIMENTAL RESULTS AND DISCUSSION

The experimental values of average mass-transfer coefficient, $\bar{k}_c$, were calculated from the rate of sublimation, m_v, through the following relation

$$\bar{k}_c = m_v R_v T_w / P_{vw} A. \tag{15}$$

The physical properties of the naphthalene were taken from Table 2 of the paper by Christian and Kezios [15]. With the definition of average Sherwood number given as

$$\overline{Sh} \equiv \frac{\bar{k}_c(x_0 - a)}{D_v}. \tag{16}$$

The experimental values of $\overline{Sh}$ can be evaluated from the measured rate of sublimation m_v.

The predicted average Sherwood number can be obtained from the analytically established heat-transfer relation through the heat and mass-transfer analogy argument. For a step-change surface-temperature distribution, the average Nusselt number based on the local Nusselt number expressed in (8) and (13) is

$$\overline{Nu} \equiv \frac{\bar{h}(x_0 - a)}{k} = K_1 s_1 (1 - \lambda_0^{s_1})^{\mu_1} (1 + \lambda_0)^{-1} Re_0^{0{\cdot}5} Pr^{1/(2+t_1)} \tag{17}$$

for laminar flow and

$$\overline{Nu} = \tfrac{10}{13} K_2 (1 - \lambda_0^{s_2})^{\mu_2} (1 + \lambda_0)^{-1} Re_0^{0{\cdot}8} Pr \tag{18}$$

for turbulent flow, where λ_0 and Re_0 are evaluated at x_0. Corresponding expressions of the average Sherwood numbers follow directly by replacing $\overline{Nu}$ and Pr by $\overline{Sh}$ and Sc (Schmidt number) respectively.

The Schmidt number of naphthalene in air is 2·40 at the average temperature 78°F in the present investigation. Appropriate calculations thus show the predicted Sherwood numbers as

$$\overline{Sh} = 0{\cdot}65\, Re_0^{0{\cdot}5}\ (\lambda_0 = 0{\cdot}25) \tag{19}$$

$$\overline{Sh} = 0{\cdot}50\, Re_0^{0{\cdot}5}\ (\lambda_0 = 0{\cdot}50) \tag{20}$$

for laminar flow with the Lighthill approximation of a linear radial-velocity profile and

$$\overline{Sh} = 0{\cdot}56\, Re_0^{0{\cdot}5}\ (\lambda_0 = 0{\cdot}25) \tag{21}$$

$$\overline{Sh} = 0{\cdot}43\, Re_0^{0{\cdot}5}\ (\lambda_0 = 0{\cdot}50) \tag{22}$$

for laminar flow with the approximation of a power-law velocity profile suggested by Davies. In turbulent flow, the results are

$$\overline{Sh} = 0{\cdot}0316\, Re_0^{0{\cdot}8}\ (\lambda_0 = 0{\cdot}25) \tag{23}$$

$$\overline{Sh} = 0{\cdot}0248\, Re_0^{0{\cdot}8}\ (\lambda_0 = 0{\cdot}50) \tag{24}$$

The experimental mass-transfer results for the rotating cones are shown in Fig. 2 for $\lambda_0 = 0{\cdot}25$ and in Fig. 3 for $\lambda_0 = 0{\cdot}5$. The case $\lambda_0 = 0$ corresponds to that of a uniform surface-temperature and the measurements were reported in references 6 and 8. The experimental data shown in Figs. 2 and 3 again indicate a different characteristic of mass-transfer results of the 60° cone from those of other cone models. The difference was explained by Tien and Campbell

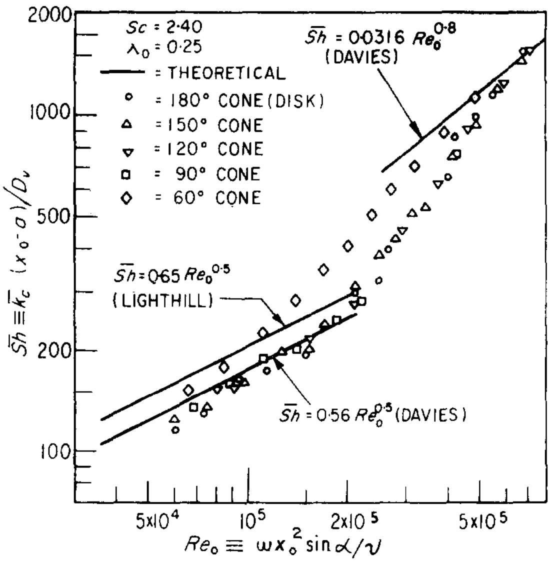

FIG. 2. The variation of the average Sherwood number with the rotational Reynolds number for non-isothermal rotating cones ($\lambda_0 = 0{\cdot}25$).

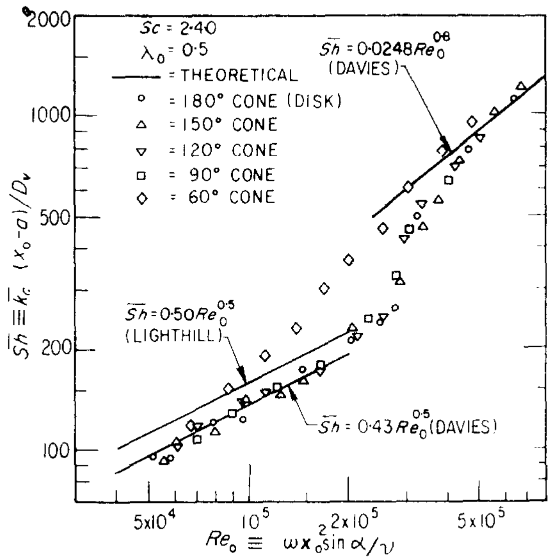

FIG. 3. The variation of the average Sherwood number with the rotational Reynolds number for non-isothermal rotating cones ($\lambda_0 = 0{\cdot}5$).

[8] and Kreith and Kneisel [9] as a result of the breakdown of boundary-layer behavior in slender cones due to the large centrifugal forces acting normal to the cone surface. The experimental results of Kreith and Kneisel show that boundary-layer flow behavior exists for rotating cones having vertex angles larger than 80 degrees.

It is expected that the mass-transfer results of 60° cone do not agree with theoretical predictions as shown in Figs. 2 and 3, since all existing theories for flow and heat transfer over rotating cones are under the boundary-layer assumption. Relatively good agreement does result between the theory and the experimental measurements for the 180°, 150°, 120° and 90° cones. In the laminar range the Davies prediction based on a power-law velocity profile shows a better agreement with experimental results than that of Lighthill with a linear velocity profile. This confirms also with the conclusion reached from the theoretical consideration since the experiments were conducted at a moderate Schmidt number ($Sc = 2{\cdot}4$). Both theories yield higher values than measurements, but the deviation from Davies result is within 15 per cent as compared to the 30 per cent in the Lighthill case. This again agrees qualitatively with the general nature, as shown in Table 1, of the comparison between exact and approximate solutions in the case of a power-law surface-temperature distribution.

The theoretical relation in the turbulent range as given in equations (23) and (24) are for the limiting case that all the conical surface is covered by turbulence. Since the upper limit of the rotational Reynolds number in the present experimental investigation corresponds to the situation the outer 70 per cent of the surface area is covered by turbulent flow, no direct comparison between theory and measurements is feasible. In theory, however, the predicted result should represent the asymptotic nature of the experimental data. The comparison shown in Figs. 2 and 3 seems to indicate that the predicted result based on Davies technique is lower than the extrapolated asymptotic experimental result by about 20 per cent. This agrees qualitatively with the recent findings by Hartnett *et al.* [17], who made a critical comparison of various approaches for the turbulent case. Similar deviation in the case of uniform surface temperature ($\lambda_0 = 0$) should be observed if the correct value of K_2 ($K_2 = 0{\cdot}0215$) were used [8]. The agreement must still be regarded as relatively good in view of the many physical assumptions made in Davies analysis [7].

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Résumé—L'article concerne les caractéristiques de transport de chaleur par l'écoulement induit, laminaire ou turbulent, autour d'un cône tournant avec des distributions non-uniformes de température de surface. On considère d'abord les calculs théoriques basés sur différentes théories existantes. Deux cas sont discutés en détails: les distributions de température de surface en puissance et en marche d'escalier. De plus, le cas de la distribution en marche d'escalier est étudié expérimentalement à l'aide de la technique de la sublimation du naphtalène. La température de surface en marche d'escalier est simulée par la sublimation de la surface de même allure. Des mesures de la vitesse de sublimation à partir de cônes tournants de différents angles au sommet sont faites à la fois dans les régions laminaire et turbulente. Elles sont alors comparées avec les résultats de transport de masse prédits à partir de la relation de transport de chaleur établie analytiquement à l'aide de l'analogie entre le transport de chaleur et le transport de masse.

Zusammenfassung—Die vorliegende Arbeit befasst sich mit den Wärmeübergangseigenschaften bei der induzierten laminaren oder turbulenten Strömung um einen rotierenden Kegel mit nicht gleichförmiger Oberflächentemperaturverteilung. Zuerst wird die theoretische Berechnung, die auf verschiedenen bestehenden Theorein fusst, betrachtet. Im einzelnen werden die zwei Fälle diskutiert: die Oberflächentemperaturverteilung nach dem Potenzgesetz und durch die schrittweise Änderung. Der Fall der Verteilung bei schrittweiser Änderung wird weiterhin experimentell mit der Naphtalin-Sublimations-Technik untersucht. Die schrittweise veränderte Oberflächentemperatur wird durch eine schrittweise geänderte Sublimation an der Oberfläche simuliert. Messungen der Sublimationsgeschwindigkeit an rotierenden Kegeln mit verschiedenen Öffnungswinkeln werden sowohl im laminaren als auch im turbulenten Strömungsbereich durchgeführt. Sie werden dann mit den vorhergesagten Ergebnissen des Stoffüberganges verglichen, die sich aus der analytisch belegten Beziehung für den Wärmeübergang über den Analogiebeweis für den Wärme und Stoffübergang ergeben.

Аннотация—В статье приводятся характеристики теплообмена при ламинарном или турбулентном обтекании вращающегося конуса с неравномерным распределением температуры на поверхности. Сначала рассматриваются данные теоретических расчетов, основанных на различных существующих теориях. Подробно разбираются два случая: степенной закон и ступенчатое распределение температуры поверхности. Случай ступенчатого распределения затем изучался экспериментально на установке для сублимации нафталина. Ступенчатое распределение температуры моделируется ступенчатой сублимацией. Измерения скорости сублимации вращающихся конусов с различными углами при вершине проводились для области как ламинарного, так и турбулентного потоков. Потом они сравнивались с результатами расчетов массобмена, полученными из аналитически установленных соотношений теплообмена (пользуясь аналогией между тепло- и массообменом).