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THERMAL TRANSFER FROM A SMALL WIRE IN BOUNDARY FLOWS ABOUT A CYLINDER

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Abstract—Measurements were made of the thermal transfer from a small platinum wire in the boundary flows of air about a 1-in copper cylinder. Comparisons were drawn between the isothermal case and the condition where the surface of the cylinder was maintained at a temperature 60 degF above the nominal bulk air temperature of 100°F. The diameter of the platinum wire was approximately 0·001 in and the nominal air velocity was 8 ft/s normal to the axis of the cylinder. Measurements were made at a total of 203 positions relative to the cylinder with duplicate measurements obtained at widely different times.

NOMENCLATURE

A,	area [ft^2];
a,	velocity of sound in air [(°F)$^{-1}$];
d,	diameter [in or ft];
g,	acceleration due to gravity [ft/s^2];
h,	heat-transfer coefficient [Btu/s ft^2 degF];
k,	thermal conductivity [Btu/s ft degF];
l,	length [in or ft];
$\mathring{m}$,	weight rate of air flow [lb/s];
$\overline{Nu}$,	Nusselt number;
$\mathring{q}$,	total thermal flux [Btu/s];
$\overline{Re}$,	Reynolds number;
r,	radial position [in or ft];
r_o,	radius of cylinder [in or ft];
T,	absolute temperature [°R];
t,	temperature [°F];
U_∞,	gross air velocity [ft/s];
u,	local or point velocity [ft/s];
u_1,	local or point velocity evaluated at "edge" of boundary layer [ft/s];
x,	vertical distance from centerline of cylinder [in or ft];
x',	distance from stagnation along surface of cylinder [ft/s];
x_*,	normalized angle parameter [ft]; $x_* = \int_0^{x'} (\sigma_w/\sigma_\infty)\, \mathrm{d}x'$;
y,	horizontal distance from centerline of cylinder [in or ft];
y',	normal distance from surface of cylinder [ft];
y_*,	normalized distance parameter [ft], $y_* = \int_0^{y'} (\sigma/\sigma_\infty)\, \mathrm{d}y'$;
z_*,	angular parameter [ft], $z_* = \delta_u^2/\nu_\infty[1 - \{(\lambda - 1)u_1^2/2a_\infty^2\}]$;
δ_t,	thermal boundary-layer thickness in terms of y_* [ft];
δ_u,	velocity boundary-layer thickness in terms of y_* [ft];
η	absolute viscosity [lb s/ft^2];
λ,	function of angular position from stagnation [sec], $\lambda = z_*(\mathrm{d}u_1/\mathrm{d}x_*)$;
ν,	kinematic viscosity [ft^2/s];
σ,	specific weight [lb/ft^3];
ψ,	angle from stagnation [deg or radian].

Subscripts

a,	local airstream temperature;
c,	cylinder;
e,	experimental;
w,	wire;
∞,	airstream;
o,	reference state.

INTRODUCTION

A SERIES of measurements were made concerning the thermal transfer from a small wire in the boundary flows about a 1-in copper cylinder. Comparisons were drawn between the isothermal case and the condition where the cylinder was at a temperature 60 degF above the nominal bulk air temperature.

The early measurements obtained by King [1], supplemented by the more recent data of Cole and Roshko [2] and of Collis and Williams [3], serve to establish with reasonable accuracy the effect of wire diameter and macroscopic conditions of transverse air flow upon the thermal transfer from a small wire in a free stream of air. At large temperature differences between the wire and the fluid it is no longer reasonable to expect that linear approximations will describe the behavior since the molecular properties of the fluid change rapidly with distance from the surface of the wire. In addition, the rather large speed and temperature gradients normal to the wire may well introduce additional variables in estimating the thermal transfer in boundary flows. Venezian [4] investigated the thermal transfer from a 0·001 in platinum wire in the boundary flows about a copper cylinder 1 inch in diameter at nominal transverse air velocities of 4, 8, and 16 ft/s. The cylinder and the airstream were both at 100°F. These measurements yielded fair agreement with predictions based on the local air speed normal to the wire and information concerning the convective transfer from small wires in free-flowing streams of air. At angles from stagnation on the order of 90 degrees for the copper cylinder, a minimum in the Nusselt number for the small wire was encountered at a radial distance of approximately 0·015 in. Such a minimum is in the region between the separated boundary layer and the cylinder where reverse flow may be expected. Nearer stagnation, neither the data of Venezian [4] nor the current experimental investigations [5] were carried sufficiently close to the cylinder to establish the minimum predicted by Piercy, Richardson and Winny [6].

Venezian [4] found significant variations in the thermal transfer coefficient with temperature differences between the airstream and the wire. In addition, the possible effects of temperature and speed gradients normal to the wire exist. For the latter reason, the influence of temperature gradients in the boundary flows was investigated. Measurements of the thermal transfer from a platinum wire approximately 0·001 inch in diameter were made throughout the two-dimensional boundary flows about a 1-in diameter copper cylinder at a nominal air velocity of 8 ft/s normal to the axis of the cylinder [5]. Data were obtained with the copper cylinder at the same temperature as the airstream and with the copper cylinder at 60 degF above that of the airstream.

PREDICTIONS

In predicting the velocity field and the temperature field in the boundary flows about a cylinder at Reynolds numbers markedly in excess of unity, it is conventional to consider two regimes. The first is that ascribed to potential flow and is concerned with the behavior at a distance from the walls of the cylinder where viscous effects are not of great importance. The flow in closer proximity to the surface of the cylinder may be approximated by conventional boundary-layer theory involving linear approximations [7, 8] to the equations for the conservation of momentum, energy and material. Prandtl [7], Hiemenz [9] and Howarth [10] have obtained reasonable solutions to the basic boundary-layer equations and tabular solutions [8] are available. More recently, Itō [11] has considered the momentum boundary flows for a fluid of constant Prandtl number with thermal transfer from a two-dimensional body with constant wall temperature. In Itō's solution a power function was assumed for the variation in viscosity and thermal conductivity with temperature. In the current case, the expressions were simplified to include only the effect of temperature upon the specific weight of an ideal gas. With these approximations, the following expressions were obtained for the spatial distribution of air speed and of temperature:

$$\frac{u}{u_1} = \left(2 + \frac{\lambda}{6}\right)\left(\frac{y_*}{\delta_u}\right) - \frac{\lambda}{2}\left(\frac{y_*}{\delta_u}\right)^2 + \left(-2 + \frac{\lambda}{2}\right)\left(\frac{y_*}{\delta_u}\right)^3 + \left(1 - \frac{\lambda}{6}\right)\left(\frac{y_*}{\delta_u}\right)^4 \quad (1)$$

$$T = T_c + T_\infty\left(1 - \frac{T_c}{T_\infty}\right)\left[2\left(\frac{y_*}{\delta_t}\right) - 2\left(\frac{y_*}{\delta_t}\right)^3 + \left(\frac{y_*}{\delta_t}\right)^4\right] \quad (2)$$

Piercy [6] evaluated the heat transfer assuming the flow field was potential in a region bounded by an infinite isothermal flat plate and a cylinder. The solution over a range of conditions of interest has been reported [4].

DEFINITION OF TERMS

In order that the experimental results may not be subject to ambiguity, it is desirable to define a few terms. The experimental heat-transfer coefficient and Nusselt number from the small wire were defined as:

$$h_e = \mathring{q}/[\pi d_w l\,(t_w - t_a)] \tag{3}$$

$$Nu_e = h_e d_w/k_a = \frac{\mathring{q}}{\pi l(t_w - t_a)k_a} \tag{4}$$

It should be noted that the Nusselt number as defined does not require a quantitative knowledge of the diameter of the wire and for that reason has been employed in the presentation of the experimental results. As a result of the need for corrections for the length of the wire because of the thermal losses to the supports and for the small "temperature jump" at the interface, these effects were combined into a single correction factor in much the same way as was done previously [4]. The results are presented in terms of the corrected Nusselt number. The free-stream Reynolds number is defined as:

$$Re_{c,\infty} = \frac{d_c\mathring{m}}{A g \eta_\infty} = \frac{d_c U_\infty}{\nu_\infty} \tag{5}$$

Table 1. Typical experimental results for isothermal conditions

Position Vertical in	Position Horizontal in	Air temperature °F	Temperature difference† degF	Heat-transfer coefficient‡ Btu/s ft² degF	Nusselt number Measured‡	Nusselt number Adjusted‡ §
			Test 541A			
−0·467	0·200	100·28	53·83	$5{\cdot}034 \times 10^{-2}$	0·9641	0·9624
		100·18	80·07	5·084	0·9740	
		100·13	102·27	5·135	0·9838	
−0·470	0·200	100·05	52·37	5·020	0·9619	0·9609
		100·09	78·27	5·074	0·9721	
		100·13	102·03	5·126	0·9820	
−0·474	0·200	100·13	55·96	5·410	1·0363	1·024
		100·10	82·83	5·407	1·0359	
		100·05	105·35	5·449	1·0440	
−0·477	0·200	100·11	55·13	5·508	1·0552	1·0520
		99·90	81·67	5·551	1·0638	
		100·03	106·20	5·619	1·0766	
−0·482	0·200	100·01	57·09	5·626	1·0781	1·0762
		99·87	83·22	5·689	1·0903	
		99·84	106·80	5·729	1·0981	
−0·489	0·200	99·97	56·24	5·666	1·0858	1·0826
		99·80	82·84	5·702	1·0930	
		99·93	105·21	5·782	1·1081	
−0·499	0·200	99·93	55·88	5·643	1·0813	1·0792
		99·91	81·97	5·697	1·0918	
		99·78	105·63	5·739	1·1000	
−0·600	0·200	99·81	58·66	5·498	1·0538	1·0506
		99·81	84·89	5·550	1·0637	
		99·86	108·40	5·597	1·0727	
−0·800	0·200	99·72	58·45	5·772	1·1064	1·1023
		99·68	85·08	5·815	1·1149	
		99·66	107·80	5·881	1·1275	

† Temperature difference, $\Delta t = t_w - t_a$

‡ Heat-transfer coefficients and Nusselt numbers are reported as experimental and include corrections for finite length of wire and "temperature jump" at interface.

§ Adjusted to a uniform temperature difference of 50 degF.

Table 2. Typical experimental results for nonisothermal conditions

Position Vertical in	 Horizontal in	Air temperature °F	Temperature difference† degF	Heat-transfer coefficient‡ Btu/s ft² degF	Nusselt number Measured‡	 Adjusted‡§
			Test 530B			
−0·468	0·200	142·35	42·72	$5{\cdot}142 \times 10^{-2}$	0·9247	0·9274
		142·39	52·74	5·165	0·9287	
		142·51	63·63	5·177	0·9308	
−0·471	0·200	134·10	42·60	5·317	0·9677	0·9682
		134·01	55·04	5·335	0·9712	
		134·93	68·64	5·340	0·9707	
−0·474	0·200	126·47	44·39	5·653	1·0406	1·0160
		126·47	61·10	5·533	1·0185	
		126·48	76·27	5·552	1·0219	
−0·477	0·200	119·01	48·14	5·660	1·0535	1·049
		119·01	62·70	5·652	1·0521	
		118·95	85·29	5·704	1·0619	
−0·482	0·200	110·41	47·13	5·737	1·0819	1·0814
		110·38	65·64	5·744	1·0833	
		110·30	85·86	5·781	1·0903	

† Temperature difference, $\Delta t = t_w - t_a$.

‡ Heat-transfer coefficients and Nusselt numbers are reported as experimental and include corrections for finite length of wire and "temperature jump" at interface.

§ Adjusted to a uniform temperature difference of 50 degF.

METHOD AND RESULTS

The equipment employed in this investigation was similar to that utilized by Venezian [4], except that somewhat greater accuracy was realized in defining the relative position of the wire with respect to the axis of the cylinder. The air supply used in these investigations has been described [12] as have the speed control of the blower [13] and the temperature and velocity-measuring equipment [14, 15].

Measurements at a total of 203 different positions were made and duplicate measurements at widely different times were obtained. A total of some 33 different operating conditions were employed. For each position and operating condition measurements were made at two or more wire temperatures. A typical set of experimental measurements is set forth in Table 1 for one set of isothermal conditions and in Table 2 for one set of nonisothermal conditions. In all cases corrections were made to bring experimental measurements to a value equivalent to a 50 degF temperature rise above the local air temperature as was done with earlier data [4]. These corrections amounted to 2 per cent when the wire was at a temperature of 120 degF above the undisturbed boundary flows.

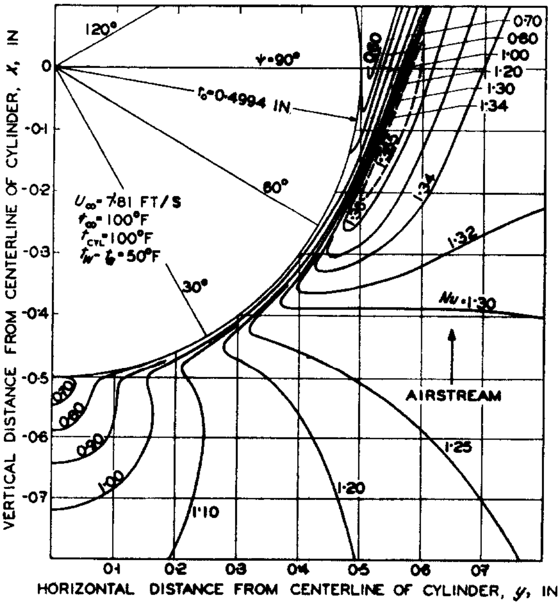

FIG. 1. Isothermal distribution of Nusselt numbers for an airstream velocity of 7·81 ft/s.

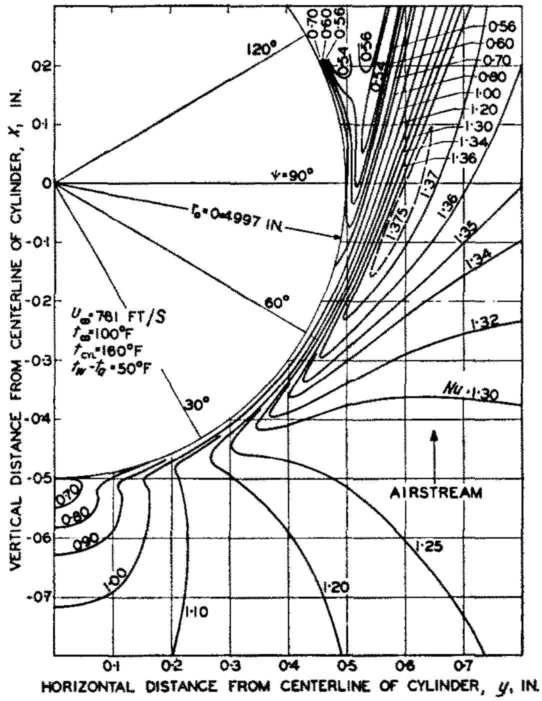

FIG. 2. Nonisothermal distribution of Nusselt numbers for an airstream velocity of 7·81 ft/s.

The measurements of Nusselt number were smoothed graphically using both the variation of the local Nusselt number from the wire as a function of position and the positions corresponding to identical Nusselt numbers as parametric variables. Figure 1 depicts the variation in the Nusselt number for the 0·001 in wire as a function of position in isothermal boundary flows about the cylinder for an undisturbed airstream velocity of 7·81 ft/s.

Similar information is depicted in Fig. 2 for the nonisothermal case where the cylinder was at 160°F and the air at 100°F for a velocity of 7·81 ft/s. It should be noted that a slightly larger diameter has been indicated as a result of the thermal expansion of the copper cylinder. The smoothed experimental data for the nonisothermal and isothermal conditions are shown in Table 3. Inspection of Table 3 indicates only small differences in Nusselt number for the isothermal and nonisothermal flow fields. These differences may well be, in part, the result of different local speed distributions in the boundary flows for the two cases. However, variations in the predicted speeds in the isothermal and

Table 3. *Nusselt number and temperature distribution about a cylinder*

Radial position in	Nusselt number†	Air temperature °F	Nusselt number†
	Isothermal	Nonisothermal	
	ψ = 0 degrees		
0·0000	0·700‡	160·0	0·718‡
0·0050	0·648	143·9	0·670
0·0100	0·6145	130·7	0·633
0·0150	0·6040	120·4	0·611
0·0200	0·6113	111·9	0·603
0·0250	0·6350	106·4	0·611
0·0300	0·6415	103·0	0·628
0·0400	0·6765	100·4	0·664
0·0500	0·707	100·0	0·698
0·0600	0·733	100·0	0·731
0·0700	0·756	100·0	0·761
	ψ = 15 degrees		
0·0000	0·791‡	160·0	0·790‡
0·0050	0·842	145·5	0·829
0·0100	0·897	131·7	0·876
0·0150	0·936	118·7	0·925
0·0200	0·955	109·0	0·956
0·0250	0·962	103·7	0·963

†, ‡ For footnotes see page 1091.

Table 3—*continued*

Radial position in	Nusselt number†	Air temperature °F	Nusselt number†
	Isothermal	Nonisothermal	
	ψ = 15 degrees		
0·0300	0·965	101·3	0·962
0·0400	0·9695	100·1	0·954
0·0500	0·973	100·0	0·954
0·0600	0·975	100·0	0·962
0·0700	0·976	100·0	0·972
	ψ = 30 degrees		
0·0000	0·872‡	160·0	0·885‡
0·0050	0·967	146·1	0·963
0·0100	1·068	132·6	1·056
0·0150	1·140	119·5	1·134
0·0200	1·173	110·2	1·171
0·0250	1·183	104·9	1·189
0·0300	1·184	102·8	1·197
0·0400	1·180	100·1	1·204
0·0500	1·178	100·0	1·202
0·0600	1·174	100·0	1·197
0·0700	1·166	100·0	1·191
	ψ = 45 degrees		
0·0000	0·913‡	160·0	0·914‡
0·0050	1·030	147·5	1·003
0·0100	1·148	135·6	1·106
0·0150	1·237	124·4	1·208
0·0200	1·283	114·0	1·273
0·0250	1·300	107·3	1·303
0·0300	1·306	103·4	1·319
0·0400	1·303	100·3	1·329
0·0500	1·298	100·0	1·322
0·0600	1·293	100·0	1·313
0·0700	1·288	100·0	1·304
	ψ = 60 degrees		
0·0000	0·879‡	160·0	0·873‡
0·0050	0·976	150·3	0·942
0·0100	1·082	140·4	1·036
0·0150	1·194	131·6	1·154
0·0200	1·285	121·1	1·253
0·0250	1·333	113·6	1·315
0·0300	1·352	107·2	1·344
0·0350	1·356	103·2	1·356
0·0400	1·358	101·5	1·362
0·0500	1·357	100·1	1·363
0·0600	1·355	100·0	1·357
0·0700	1·351	100·0	1·350
	ψ = 75 degrees		
0·0000	0·795‡	160·0	0·792‡
0·0050	0·805	153·2	0·801
0·0100	0·842	146·2	0·839
0·0150	0·928	138·6	0·920
0·0200	1·080	131·3	1·058
0·0250	1·206	124·5	1·182

†, ‡ For footnotes see page 1091.

Table 3—*continued*

Radial position in	Nusselt number†	Air temperature °F	Nusselt number†
	Isothermal	Nonisothermal	
	$\psi = 75$ degrees		
0·0300	1·291	118·1	1·270
0·0350	1·332	112·4	1·319
0·0400	1·363	108·1	1·342
0·0450	1·365	104·9	1·357
0·0500	1·365	102·6	1·367
0·0600	1·360	100·3	1·372
0·0700	1·354	100·0	1·374
0·0800	1·347	100·0	1·372
	$\psi = 90$ degrees		
0·0000	0·725‡	160·0	0·742‡
0·0050	0·650	155·4	0·643
0·0100	0·604	151·7	0·587
0·0150	0·582	148·6	0·559
0·0200	0·592	145·9	0·557
0·0250	0·650	143·4	0·586
0·0300	0·731	141·0	0·651
0·0350	0·824	138·5	0·732
0·0400	0·912	135·9	0·824
0·0450	1·008	132·9	0·927
0·0500	1·102	132·9	1·034
0·0600	1·259	125·3	1·212
0·0700	1·3455	113·1	1·308
0·0800	1·366	106·6	1·349
0·0900	1·366	102·5	1·366
0·1000	1·364	100·7	1·374
0·1100	1·361	100·1	1·376
	$\psi = 105$ degrees		
0·0000	—§	160·0	—
0·0050		151·0	0·732‡
0·0100		146·7	0·616
0·0150		142·8	0·583
0·0200		139·6	0·571
0·0300		134·3	0·559
0·0400		129·9	0·551
0·0500		127·2	0·545
0·0600		126·2	0·535
0·0700		126·1	0·530
0·0800		127·2	0·559
0·0900		129·1	0·628
0·1000		131·0	0·735
0·1100		131·6	0·882
0·1200		128·7	1·033
0·1300		123·1	1·160
0·1400		117·2	1·242
0·1500		111·7	1·298
0·1600		107·2	1·333
0·1700		104·3	1·353
0·1800		102·4	1·363

† Based on a wire temperature 50 degF above the local airstream temperature.
‡ Extrapolation to this value is questionable.
§ Measurements for the isothermal case were not taken in this region.

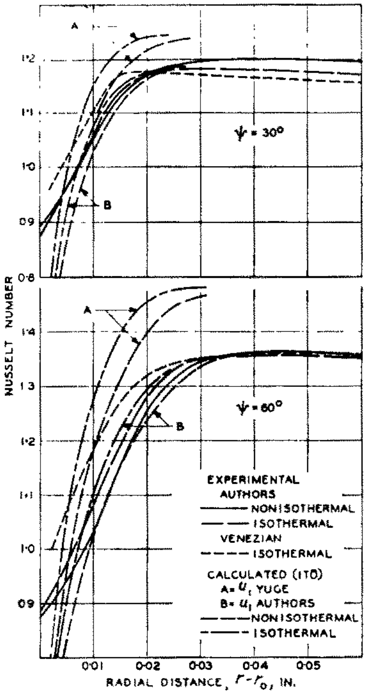

FIG. 3. Variation in Nusselt number with radial position for angles of 30 and 60 degrees from stagnation for an air velocity of 7·81 ft/s.

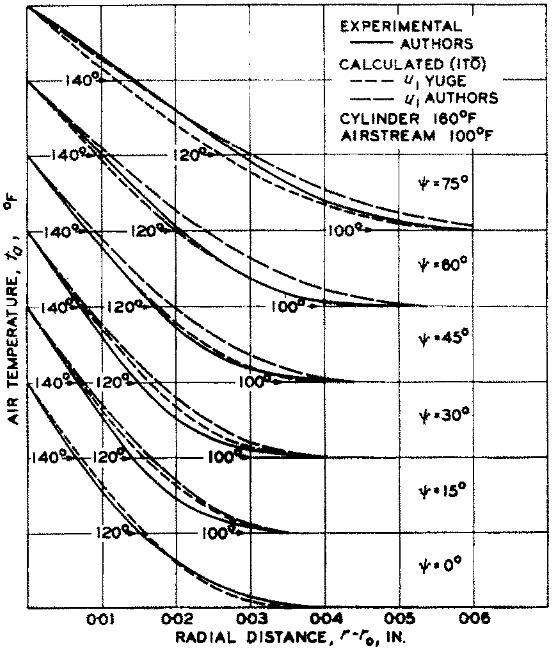

FIG. 4. Comparison of predicted and measured temperature distribution for several angles from stagnation for a free-stream Reynolds number of 3500.

nonisothermal fields are not reflected in the differences in Nusselt number shown for the experimental results in Fig. 3. The variation in Nusselt number with radial position for angles of 30 and 60 degrees from stagnation is shown in Fig. 3 for an air velocity of 7·81 ft/s. The experimental values are compared with values calculated using Itō's method [11] and employing boundary-layer velocity distributions presented by Yuge [16] as well as the author's velocity distributions [5].

The experimental temperature distribution in the boundary flow of air is shown in Fig. 4 for stagnation and for several different angles measured from stagnation. Also included is the temperature calculated [11] from equation (2) using the speed distribution measured by the authors, and fair agreement between the predicted and measured temperature distribution was realized. The predicted values, utilizing Yuge's [16] boundary-layer velocity distributions

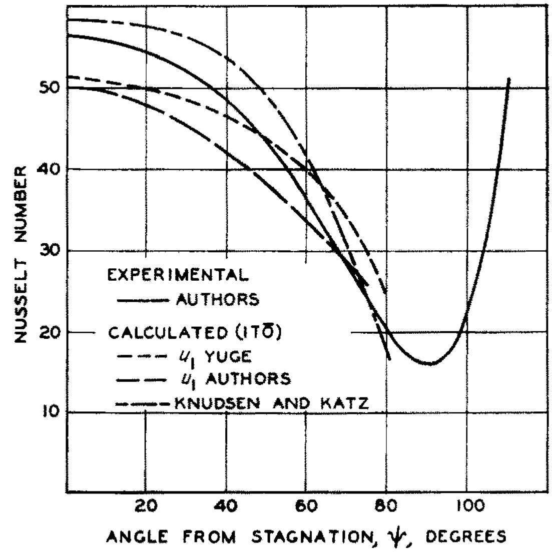

FIG. 5. Local thermal transfer from the cylinder for a free-stream Reynolds number of 3500.

[11], were as much as 25 per cent higher than the experimental values as the outer edge of the boundary flow was approached.

The local thermal transfer from the 1-in copper cylinder may be evaluated from the limiting radial temperature gradient around the cylinder. The local Nusselt number may be evaluated from:

$$Nu_{c,\infty} = \frac{2h_c r_0}{k_\infty} = \frac{-2k_a r_0}{k_\infty(t_\infty - t_c)} \left(\frac{\partial t_a}{\partial r}\right)_{r_0} \quad (6)$$

These indirectly measured values are shown in Fig. 5 along with calculated values based on Itō's method [11]. The latter information involved the authors' measured, as well as Yuge's [16], speed distributions at the edge of the boundary layer. Semi-empirical values of Knudsen and Katz [17] were also included in Fig. 5. Reasonable agreement between the results of Knudsen and the present indirect measurements of local Nusselt number is indicated.

CONCLUSION

It appears that there is no indication of a significant effect due to a temperature gradient normal to a small wire upon its thermal transfer. Therefore, values based upon isothermal behavior can be employed for nonisothermal conditions as long as knowledge of the local temperature is available. Predictions at relatively low speeds following the method of Itō [11] appear to be satisfactory although they are not much more accurate for isothermal conditions than Howarth's solution [10]. The local variations in thermal transfer about a cylinder are only in fair agreement with the semi-empirical predictions of Knudsen [17] or with the theoretical analysis of Itō [11] utilizing experimentally measured speed distributions at the outer edge of the boundary flows.

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Résumé—On a mesuré le transport thermique à partir d'un petit fil de platine dans un écoulement d'air au voisinage d'un cylindre de cuivre de 25 mm de diamètre. On a comparé le cas isotherme et celui où la température de la surface du cylindre est de 33 degC plus élevée que celle de l'air, égale à 38 °C. Le diamètre du fil de platine était approximativement égal à 25 microns et la vitesse de l'air était égale à 2,40 m/s et perpendiculaire à l'axe du cylindre. Des mesures ont été effectuées à 203 positions au total par rapport au cylindre avec des mesures en double à des temps largement différents.

Zusammenfassung—In dieser Arbeit wird der Wärmeübergang von einem dünnen Platindraht in der Grenzschicht einer Luftströmung um einen Kupferzylinder von 25 mm Durchmesser gemessen. Der isotherme Fall wird mit jenen Bedingungen verglichen, bei denen die Zylinderoberfläche eine Übertemperatur von 33 degC über der Freistromtemperatur von 38 °C hatte. Der Platindraht hatte einen Durchmesser von 0,025 mm und die nominelle Luftgeschwindigkeit betrug 0,24 m/s normal zur Zylinderachse. Insgesamt wurden Messungen an 203 Stellungen relative zum Zylinder durchgeführt mit Doppelmessungen zu ganz verschiedenen Zeiten.

Аннотация—Выполнены измерения теплообмена платиновой проволочки в пограничном слое при обтекании воздухом 1-дюймового медного цилиндра. Проведено сравнение изотермического случая со случаем, когда температура цилиндра поддерживалась более высокой, в сравнении с номинальной температурой воздуха, составлявшей 100°F.

Диаметр платиной проволочки был приблизительно 0,001 дюйма, а номинальная скорость воздуха по нормали к оси цилиндра составляла 8 ft/s.

В целом проведены измерения для 203 положений по отношению к цилиндру с повторением замеров через значительные промежутки времени.