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AN EXPERIMENTAL STUDY OF CENTRIFUGALLY DRIVEN FREE CONVECTION IN A RECTANGULAR CAVITY

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Abstract—Centrifugally driven thermal convection has been studied experimentally in a rectangular cavity of length 27·94 cm, height 2·62 cm, and width 2·54 cm. The cavity was heated from above and cooled from below and rotated about a vertical axis passing through the center point of the cavity. The cavity was filled with silicone oils having Prandtl numbers of 7 and 3000, and rotated up to 565 rev/min.

The Nusselt number for heat transfer from the top to bottom surfaces varied as the 0·4 power and the 0·25 power of the imposed temperature difference for the low and high Prandtl number fluids, respectively, and as the 0·25 and 0·3 powers of the centrifugal acceleration evaluated at the outer edge of the cavity. A dimensionless radial centerline temperature gradient was obtained and found to be independent of both rotational rate and imposed temperature difference.

NOMENCLATURE

- A, centrifugal acceleration $\omega^2 a$ [cm s^{-2}];
- a, half-length of rectangular cavity [cm];
- b, height of test section [cm];
- C_p, specific heat [cal g^{-1} °C^{-1}];
- g, gravitational acceleration, = 980 cm s^{-2};
- i, electrical current [A];
- k, thermal conductivity [cal s^{-1} cm^{-1} °C^{-1}];
- Nu, Nusselt number;
- Q, heat-transfer rate [W];
- R, electrical resistance [Ω];
- r, distance from axis of rotation [cm];
- r^*, dimensionless distance r/a;
- T, temperature [°C].

Greek symbols

- α, coefficient of thermal expansion [°C^{-1}];
- β, thermal Rossby number $\alpha\Delta T/8$;
- ΔT, temperature difference $T_T - T_B$ [°C];
- ε, Ekman number $2\nu/(\omega b^2)$;
- θ, dimensionless temperature $(T-T_B)/(T_T-T_B)_{\text{local}}$;
- ν, kinematic viscosity [cm^2 s^{-1}];
- ρ, density [g cm^{-3}];
- σ, Prandtl number;
- ω, angular velocity [s^{-1}].

Subscripts

- Gr_ω, rotational Grashof number $\omega^2 a\alpha\Delta T b^3 \nu^{-2}$;
- Q_{cond}, heat transfer by conduction alone;
- Q_L, heat loss;
- Q_{net}, heat transfer through test section $Q_T - Q_L$;
- Q_T, total heat input, $= i^2R$;
- Ra_g, gravitational Rayleigh number $\sigma g\alpha\Delta T b^3\nu^{-2}$;
- Ra_ω, rotational Rayleigh number $\sigma\omega^2 a\alpha\Delta T b^3\nu^{-2}$;
- T_{ave}, average fluid temperature;
- T_B, bottom surface temperature;
- T_{T1}, T_{T2}, T_{T3}, top surface temperatures at positions 1, 2, and 3, respectively;
- $T_{P1}, T_{P2}, T_{P3}, T_{P4}, T_{P5}$, temperatures measured by probes at positions 1 through 5, respectively;
- $\theta_1, \theta_2, \theta_3, \theta_4, \theta_5$, dimensionless temperatures at positions 1 through 5, respectively.

INTRODUCTION

CONVECTION is produced in a fluid by the coupling of a density gradient and an acceleration which is normal to the gradient. An example of this is free convection in which the gravitational acceleration is normal to an imposed horizontal temperature gradient. In a similar manner the centrifugal acceleration can induce convection in a rotating fluid. Consider, for example, a fluid in a closed container which is rotating about a fixed axis at a constant rate; if the system is isothermal it will be in solid body rotation. Now impose a temperature gradient normal to the centrifugal acceleration, say, for example, parallel to the axis of rotation. Motion in the fluid relative to solid body rotation will be induced and this motion will produce an increase in heat transfer over that which would occur in the absence of convection. Since the centrifugal acceleration can be made very large, the possibility of high rates of heat transfer exists. It is thus of interest to determine the rate of heat transfer and the temperature distribution in such rotating fluids and to compare the behavior to previously studied problems in stationary natural convection.

It was shown by Schmidt that significant heat-transfer rates could be effected by means of internal water cooling of turbine blades [26]. Since that time there have been several studies on convection in a closed loop rotating thermosyphon [5, 23] and in rotating tubes [3, 13, 19–22, 25, 27]. These works include mathematical analyses of tubes which rotate about an axis either normal [20, 21] or parallel [22] to the axis of the tube. In each of the experimental

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investigations [3, 13, 19, 25] motion in the tube is produced both by the action of the centrifugal acceleration acting on a density gradient and by an externally imposed pressure gradient.

Another class of problems has also been studied, viz. convection in a right circular cylinder which rotates about a vertical axis and which is heated from above and cooled from below. Motion relative to solid body rotation is thus solely induced by the coupling of the vertical temperature gradient and the centrifugal acceleration acting in a horizontal plane. Although most of the investigations were mathematical [9–12, 24] there has been one recent experimental study [1, 2]. This geometry has received interest because it is amenable to mathematical analysis and to interpretation of experimental data. When the Ekman number is small (large rotational Reynolds number which occurs at high rotational rates) the vertical temperature gradient coupled with the Coriolis acceleration drives a tangential flow relative to solid body rotation; this tangential flow induces a secondary radial and axial motion which convects heat between the warm and cold surfaces. When the ratio of cylinder radius to height is large, the temperature is independent of radial position except in a region near the side wall of the cylinder.

A related problem, viz. convection near a rotating plate has also been treated mathematically [4, 14–18].

In this paper we describe an experimental study of centrifugally driven convection in a rectangular cavity. A sketch of the geometry being considered is shown in Fig. 1(a). The cavity is completely closed, filled with

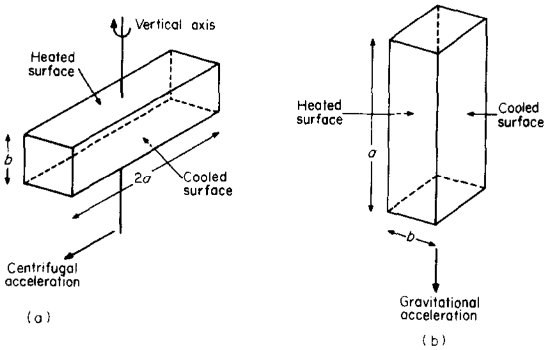

FIG. 1. (a) Horizontal rotating cavity. (b) Stationary vertical cavity.

fluid, and rotated about a vertical axis passing through the mid-point of the cavity. The top surface is heated and the bottom is cooled. The system has the following characteristics. First, it is enclosed and no external pressure gradient is imposed. Thus, when the fluid is not heated, the system is in solid body rotation. In such a system the characteristics of centrifugally driven thermal convection can be studied without the complicating influence of an externally produced flow. Secondly, since the cavity is not axially symmetric, a strong tangential flow relative to solid body rotation cannot be induced and the system resembles geometries of practical interest more closely than a rotating cylinder. Thirdly, the results of study on this geometry allow comparisons to be made between rotating and non-rotating natural convection, since, as can be seen from Fig. 1(b), the system is analogous to natural convection in a vertical, stationary cavity which is heated and cooled on opposite sides.

Measurements were made on the rate of heat transfer from the top, heated surface to the bottom, cooled surface and of the temperature distribution along the centerline of the cavity.

EXPERIMENTS

The experiments were carried out in a rectangular cavity of height 2·62 cm, width 2·54 cm, and length 27·94 cm. Two silicone oils (Dow Corning 200 Fluids) having nominal viscosities of 0·65 and 350 cS were used. The cavity was rotated up to 565 rev/min or up to rotational Grashof numbers of 10^9. (The rotational Grashof number is defined by replacing the acceleration of gravity in the normal Grashof number by the centrifugal acceleration at the outer edge of the cavity.)

Apparatus

Details of the apparatus are shown in Fig. 2. The rectangular cavity test section is formed by two aluminum plates and a plastic sidewall. The top boundary is a rectangular slab of aluminum 30·48 × 5·08 × 1·27 cm thick, with a heating element imbedded in the top side. The bottom boundary is a disk, 35·56 cm in diameter and 1·27 cm thick drilled to locate and hold the test section centered on the horizontal turntable.

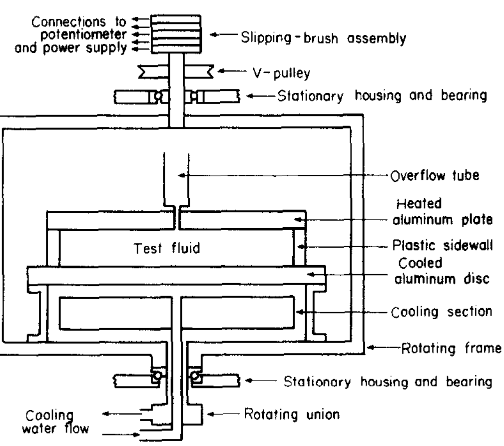

FIG. 2. Schematic diagram of apparatus.

The sidewall is made from four separate pieces of 1·27 cm thick cast acrylic plastic cemented together to form a box with inside dimensions 27·94 × 2·54 cm and then cut down to a height of 2·54 cm.

The test section was assembled together using 20 $\frac{1}{4}$–20 NC nylon studs threaded into tapped blind holes in the lower disk, passing up through holes drilled in the acrylic sidewall, and fastened above the top aluminum surface with washers and nuts.

A seal was effected between aluminum and plastic surfaces by O-rings pressed into grooves in the aluminum surfaces.

Table 1. Physical properties of Dow Corning 200 fluid

	Low viscosity oil	High viscosity oil
*Density (g/cm^3)	0·761	0·970
*Coefficient of thermal expansion (°C^{-1})	0·00134	0·00096
*Thermal conductivity cal/(s cm °C)	0·00024	0·00038
*Specific heat C_p cal/(g °C)	0·349	0·349
*Kinematic viscosity (cS)	0·65	350
†Kinematic viscosity (cS) constants for equation $\log_{10} \nu = AT+B$	$A = -4{\cdot}44 \times 10^{-3}\,°C^{-1}$ $B = -9{\cdot}48 \times 10^{-2}$	$A = -8{\cdot}43 \times 10^{-3}\,°C^{-1}$ $B = 2{\cdot}723$

*Value at room temperature supplied by manufacturer.
†Determined by Ostwald Viscometer Technique.

After assembly, the inside dimensions of the test section were 27·94 × 2·62 × 2·54 cm. An overflow tube was screwed into a tapped hole in the center of the top aluminum plate to allow for filling the cavity and to provide an outlet for expansion and contraction of fluid.

The heating element in the top surface is a 33-gage chromel–alumel "Thermopak" Thermocouple pair connected in series. The bottom disk was cooled by a flow of water which enters the rotating frame through a rotary union, flows around a baffle in the cooling section, and back out the union.

As noted above, the top plate was heated electrically. However, since it was made of $\frac{1}{2}$ in aluminum, the desired constant temperature boundary condition was obtained under most conditions. This is discussed further in the section on "Results".

The rotating frame and test section are free to rotate in ball bearings in a stationary housing in the shape of a box open at one end. The lower axle carries the coolant flow, while the upper axle carries wiring to a slip ring–brush arrangement at the top where signals are removed from the rotating components. The upper axle also carries a pulley which is driven at constant speed by an electric motor acting through a gearbox and belt drive.

Surface temperatures were monitored by three copper–constantan junctions inbedded in each of the top and bottom aluminum surfaces. The top surface junctions are at distances of 2·54, 6·35 and 11·43 cm from the center. The bottom surface junctions are located at distances of 0, 6·98 and 13·34 cm from the center.

Five thermocouple probes are introduced into the test section through adapters mounted halfway up the plastic sidewall. The adapters provide for sealing around the 0·040-in dia probe sheaths and also permit adjustment of insertion depth. The probes are produced by Thermo-couple Products Company and have an exposed copper–constantan junction at one end with an internal connection to extension wires at the other. Errors caused by conduction along the wires are minimized since the probes were normal to the imposed temperature gradient.

Runs were made with and without the thermocouple probes. The probes had no measurable influence on the heat transfer–temperature difference relationship.

Of the five measuring junctions, the outer four are located at distances of 2·54, 6·98, 10·80 and 13·65 cm from the center throughout the experiments. The fifth probe is in the center for experiments with low viscosity oil, and 1·27 cm from the center for experiments with high viscosity oil. The location of the center thermocouple was changed in an attempt to determine the extent of the center "end effect" zone.

Thermocouple voltages are read on a precision potentiometer with an accuracy of better than 1 μV.

The physical properties of the Dow Corning fluids used in the study are shown in Table 1.

Experimental procedure

The variables controlled during experimental work were current to the heater, cooling water temperature, and rotational speed. The current and coolant temperatures were adjusted to give a range of temperature difference from 10 to 25°C. Rotational speed was adjusted by selecting a pulley combination. Speeds of 0, 264, 430 and 565 rev/min were used.

Top and bottom surface temperatures were adjusted during experiments such that the average of the two temperatures was equal to room temperature. Since physical properties, particularly viscosity, were evaluated at this average temperature, they remain relatively constant throughout, making runs at constant rotational speed equivalent to runs at constant Ekman number.

Total heat input was calculated from resistance heating. The heat lost to the surroundings through insulation and the heat conducted down the acrylic sidewall were measured by filling the test section with a solid piece of plastic which has a known thermal conductivity and which cannot convect heat during rotation. The heat loss, calibrated against temperature difference, is subtracted from total heat input to yield Q_{net}, the heat transferred through the fluid in the test section by conduction and convection together. A direct measurement of temperature difference is made using a technique incorporating a measurement of the

Table 2. Heat-transfer results

Run No.	Q_T (W)	Q_{net} (W)	T_B (°C)	T_{T1} (°C)	T_{T2} (°C)	T_{T3} (°C)	ΔT (°C)	Nu	$\beta \times 10^3$	$\varepsilon \times 10^5$
	264 rev/min, 0·65 cS oil									
1	7·66	6·06	17·48	28·03	27·42	26·86	9·96	22·5	1·67	6·73
2	11·14	9·00	15·35	30·03	29·10	28·23	13·77	24·1	2·31	6·75
3	15·20	12·51	13·36	32·26	31·06	29·82	17·69	26·1	2·96	6·75
4	20·62	17·28	11·14	35·18	33·65	31·63	22·35	28·5	3·74	6·74
5	23·86	20·19	10·01	36·65	34·77	32·77	24·72	30·1	4·14	6·74
	430 rev/min, 0·65 cS oil									
6	8·16	5·95	19·83	28·81	28·19	27·67	8·39	26·2	1·41	4·07
7	12·92	10·08	17·24	30·46	29·49	28·54	12·26	30·3	2·05	4·10
8	18·78	15·27	14·62	32·38	31·12	29·60	16·41	34·3	2·75	4·12
9	24·67	20·57	13·68	35·38	33·72	31·80	19·95	38·1	3·34	4·08
10	31·99	27·05	10·61	38·18	35·94	33·18	25·15	39·7	4·21	4·10
	565 rev/min, 0·65 cS oil									
11	9·67	7·02	19·78	29·08	28·47	27·76	8·66	29·9	1·45	3·09
12	15·71	12·01	17·76	31·47	30·40	29·25	12·61	35·1	2·11	3·10
13	22·98	18·07	15·67	34·34	32·95	31·18	17·15	38·9	2·87	3·09
14	30·35	24·41	13·47	36·61	34·55	32·29	21·01	42·9	3·52	3·10
15	37·00	30·18	11·42	38·18	35·82	33·21	24·32	45·8	4·07	3·11
	264 rev/min, 350 cS oil									$\varepsilon \times 10^2$
16	3·86	2·15	18·17	29·12	28·85	28·57	10·68	4·67	1·28	3·53
17	5·18	3·05	16·13	30·14	29·19	29·54	13·73	5·15	1·65	3·56
18	6·80	4·12	13·96	32·00	31·60	31·10	17·61	5·43	2·11	3·58
19	8·71	5·38	11·59	34·47	33·93	33·20	22·28	5·61	2·67	3·58
20	9·75	6·11	9·75	34·97	34·35	33·55	24·54	5·78	2·94	3·63
	430 rev/min, 350 cS oil									
21	5·38	2·81	18·18	29·12	28·78	28·50	10·62	6·13	1·28	2·17
22	6·99	3·91	16·63	30·80	30·38	30·00	13·76	6·59	1·65	2·17
23	8·69	5·13	15·05	32·23	31·72	31·22	16·67	7·14	2·00	2·17
24	10·83	6·65	12·69	33·90	33·22	32·52	20·52	7·52	2·46	2·19
25	12·81	8·11	10·99	35·51	34·68	33·83	23·68	7·94	2·84	2·20
	565 rev/min, 350 cS oil									
26	6·93	3·59	18·87	30·49	30·08	29·77	11·24	7·41	1·35	1·62
27	9·05	4·92	16·82	31·57	31·01	30·49	14·20	8·04	1·70	1·64
28	11·00	6·13	14·91	32·49	31·94	31·26	16·99	8·37	2·04	1·65
29	13·39	7·63	12·75	33·82	33·03	32·37	20·32	8·72	2·44	1·67
30	15·94	9·32	10·86	35·32	34·39	33·65	23·59	9·16	2·83	1·68

resultant net voltage of two junctions, one in the top surface and one in the bottom. Experimental runs are continued until the thermal conditions reach steady state, normally 3–6 h, when final readings of all thermocouples and current are taken. These measurements give values for top, bottom and interior temperatures, temperature difference, and total heat input.

RESULTS AND DISCUSSION

Heat transfer

From the experiments values were obtained for the temperatures of the top and bottom aluminum surfaces of the cavity, and the net heat flux from top surface to bottom surface at a given rotational rate. Experimental data are presented in Table 2.

It was desired to have both the top and bottom surfaces isothermal. The bottom surface temperature as measured by thermocouples at three radial positions usually varied by no more than 0·05°C and never more than 0·1°C. However, the temperature of the top plate, which was heated electrically, varied somewhat with radial position as can be seen in Table 2. In general, the overall variation in top surface temperature increased strongly with increasing T and weakly with increasing rotational rate, from about 1·5°C at low speeds and temperature differences to about 5°C at high speed and large T. An average top temperature was calculated and used in analyzing the heat-transfer results. Although this temperature variation will introduce some error into the results, it is not expected to have a significant influence on the dependence of the Nusselt number on the rotational rate or on the imposed temperature difference.

The following characteristic dimensionless groups were evaluated from these data using fluid properties evaluated at the mean of the top and bottom plate temperatures: the Nusselt number Nu, the thermal Rossby number β, and the Ekman number ε. The Nusselt number is the ratio of the net heat flux, Q_{net}, to the heat which is conducted across the fluid when the cavity is stationary, Q_{cond}. This latter quantity is given by $Q_{cond} = 0{\cdot}0271\Delta T$ (low viscosity oil) and $Q_{cond} = 0{\cdot}0431\Delta T$ (high viscosity oil) for the cavity being studied.

The Nusselt number is shown as a function of Rossby number (which is proportional to temperature difference) at fixed rotational rates in Fig. 3 (low viscosity oil) and in Fig. 4 (high viscosity oil). The

Nusselt number is identically equal to one for all imposed temperature differences when the cavity is not rotating since heating is from above and the fluid is thus stably stratified.

By comparing Figs. 3 and 4 it is seen that the Nusselt number for the low viscosity oil is approximately five times that of the high viscosity oil at the same conditions.

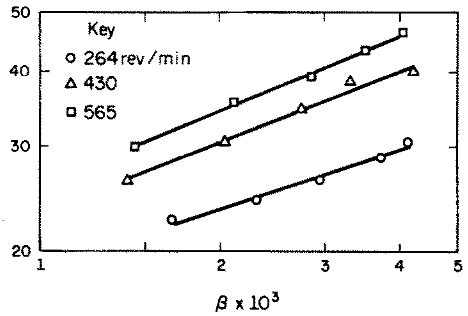

FIG. 3. Nusselt number, low viscosity oil.

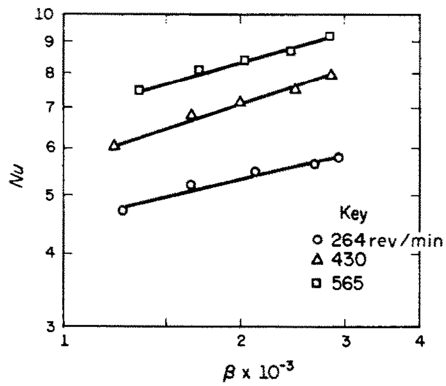

FIG. 4. Nusselt number, high viscosity oil.

Straight lines were fitted through the data of Figs. 3 and 4 by means of a least square fit. The slopes of the lines for the low viscosity oil are 0·327, 0·392 and 0·409 for 264, 430 and 565 rev/min respectively. The slopes for the high viscosity oil are 0·236, 0·325 and 0·274 for the same rotational rates. This indicates that the Nusselt number depends on the temperature difference approximately to the 0·4 and the 0·25 power for the low and high viscosity oils, respectively. (This is obtained by approximating the average of the above slopes.)

The data are cross plotted against the Ekman number (proportional to the reciprocal of the rotational rate) in Fig. 5 for the low viscosity oil and in Fig. 6 for the high viscosity oil. The average slope of the lines in Fig. 5 is $-0{\cdot}5$, which indicates that the Nusselt number depends on the square root of the angular velocity for the low viscosity oil. The average slope in Fig. 6 is $-0{\cdot}6$ so that the Nusselt number depends on the 0·6 power of the rotational rate for the high viscosity oil.

Thus it is seen that for the range of parameters investigated in this study that the Nusselt number can be expressed by

$$Nu = 2{\cdot}28\beta^{0\cdot4}\varepsilon^{-0\cdot5} = 0{\cdot}702\frac{\alpha^{0\cdot4}b}{\nu^{0\cdot5}a^{0\cdot25}}\Delta T^{0\cdot4}A^{0\cdot25} \quad (1)$$

for the low viscosity oil and

$$Nu = 3{\cdot}37\beta^{0\cdot25}\varepsilon^{-0\cdot6} = 1{\cdot}32\frac{\alpha^{0\cdot25}b^{1\cdot2}}{\nu^{0\cdot6}a^{0\cdot3}}\Delta T^{0\cdot25}A^{0\cdot3} \quad (2)$$

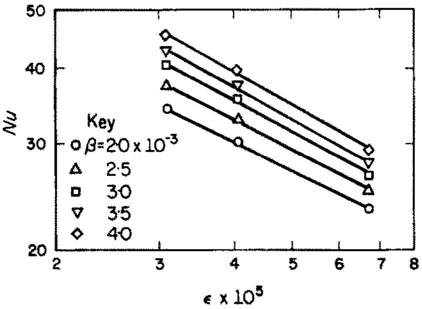

FIG. 5. Nusselt number, low viscosity oil.

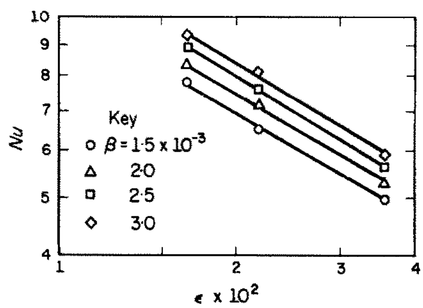

FIG. 6. Nusselt number, high viscosity oil.

for the high viscosity oil. Although there is some uncertainty in the exact values of the exponents in equations (1) and (2), it can be said that the exponents of ΔT and of A are different and furthermore, that the exponents of each of these quantities differ for the low and high viscosity oils. The significance of these differences is discussed further below. The coefficients were determined by means of a least square fit and correlate the Nusselt numbers to standard deviations of 0·76 and 0·14 for equations (1) and (2) respectively. The variable A, the centrifugal acceleration at the outer edge of the cavity, was introduced into the above expressions in order to facilitate a comparison with stationary natural convection. Although the expressions are useful in determining the dependence on the imposed temperature difference and the rotational rate, the dependence on the cavity dimensions and the Prandtl number is still unknown since these were held fixed in the experiments.

The difference in form between equations (1) and (2) can probably be explained by a consideration of the expected flow patterns in the two cases. The Ekman number for the low viscosity oil is of the order of 10^{-5}; it is to be expected from experience with other rotating systems [9–11] that boundary layers would exist under these conditions. For the high viscosity oil, however, the Ekman number is 500 times greater, and boundary layers probably do not form, or if they do form they would fill a much larger fraction of the volume.

The above results might be compared to stationary natural convection. Two studies will be used for this comparison [6, 8]. In each of these studies stationary convection was studied in a vertical slot with one horizontal dimension being much larger than the horizontal distance between the hot and cold plates. Thus, the work is not completely analogous to the present study in which dimensions normal to the acceleration are of the same order of magnitude. Eckert and Carlson [6] determined that the Nusselt number depends on the 0·3 power of the Grashof number for stationary convection; therefore, it depends on both the applied temperature difference and on the acceleration of gravity to the 0·3 power. As can be seen from equations (1) and (2), the Nusselt number depends on the 0·4 and the 0·25 power of the temperature and on the 0·25 and the 0·3 power of the centrifugal acceleration for the low and high viscosity fluids respectively. There are thus small but yet significant differences between the dependences obtained in the rotating channel and those observed previously by others in stationary natural convection.

The differences between rotating and non-rotating convection are caused by two factors. First, the local centrifugal acceleration is a strong function of position whereas the acceleration of gravity is almost constant. Secondly, the Coriolis acceleration influences rotating convection. This latter effect is not expected to be as important in the rotating cavity as in other rotating geometries such as a cylinder since in the channel being considered here a strong secondary flow cannot develop since the channel is not axisymmetric. In an axisymmetric cylinder the dependences of the flow and heat transfer on the imposed temperature difference and on the rotational rate are significantly different from those obtained in stationary free convection [1, 2, 9, 11].

Horizontal centerline temperature profile

The temperature along the centerline of the channel was measured with a series of thermocouple probes; results are given in Table 3. A non-dimensional temperature, θ, is shown in Figs. 7 and 8 for the low and high viscosity oils, respectively.

This non-dimensional temperature is defined using the temperature differences between the top and bottom plates.

As noted above and as seen in Table 2, the temperature of the top heated surface was not always perfectly isothermal. In order to take this variation into account in the centerline temperature profile, a dimensionless temperature for each probe was calculated as follows. The upper surface temperature was assumed to be linear with r, and fitted to a straight line

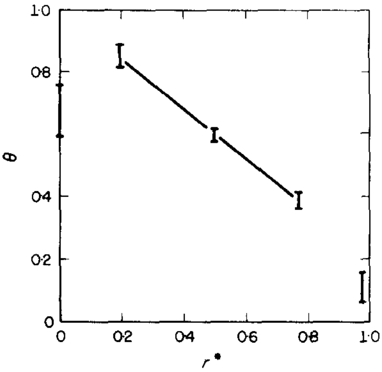

FIG. 7. Dimensionless centerline temperature profile, low viscosity oil.

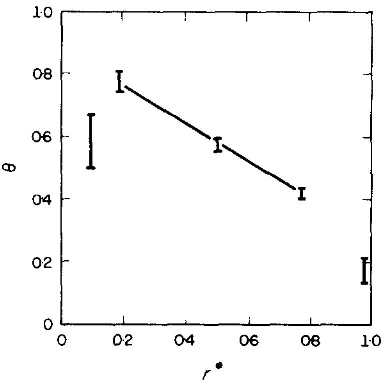

FIG. 8. Dimensionless centerline temperature profile, high viscosity oil.

equation. Then a local ΔT was calculated by using the equation to calculate the temperature of the surface directly above the probe junction. After subtracting the average bottom surface temperature, this became ΔT_{local}, and dimensionless temperature θ was calculated as

$$\theta = \frac{T - T_B}{(T_T - T_B)_{\text{local}}}$$

Figures 7 and 8 both include data taken at all non-zero rotational rates and all values of imposed temperature difference. It is seen that the dimensionless centerline temperature profile is independent of these two variables for the conditions of these experiments. Furthermore, in each case the temperature varies approximately linearly with radial position for dimensionless distance between 0·2 and 0·75.

The gradient, $d\theta/dr^*$, has approximate values of $-0{\cdot}6$ for the high viscosity oil and $-0{\cdot}8$ for the low viscosity oil. The dimension r^* is measured from the center of rotation, and so a gradient of $-0{\cdot}6$ in the rotating cavity is equivalent to $+0{\cdot}6$ in a vertical stationary slot where r^* is measured from the bottom of the slot.

It is interesting to note that the radial dimensionless temperature gradient is not only independent of the rotational rate and the imposed temperature difference for the range of variables studied, but the gradient is not too dissimilar to that for non-rotating natural

Table 3. Centerline temperature profile (temperatures in °C)

Run No.	T_{P1}	T_{P2}	T_{P3}	T_{P4}	T_{P5}	θ_1	θ_2	θ_3	θ_4	θ_5
1	24·65	26·78	23·53	21·12	18·68	0·661	0·885	0·609	0·386	0·132
2	26·51	28·20	23·63	20·27	16·88	0·739	0·880	0·604	0·380	0·124
3	27·71	29·90	24·09	19·62	15·10	0·734	0·878	0·608	0·377	0·110
4	27·55	32·29	24·87	18·29	12·62	0·655	0·880	0·617	0·345	0·076
5	30·14	33·06	24·99	18·47	11·46	0·727	0·868	0·608	0·368	0·067
6	26·28	27·45	24·89	22·96	20·97	0·697	0·853	0·605	0·397	0·152
7	27·28	28·29	24·61	21·78	18·70	0·732	0·839	0·604	0·398	0·135
8	27·19	29·58	24·36	20·54	16·51	0·678	0·843	0·596	0·391	0·132
9	30·91	31·93	25·57	20·99	15·99	0·760	0·843	0·598	0·400	0·134
10	28·62	33·37	25·03	19·95	13·25	0·622	0·827	0·576	0·408	0·124
11	25·86	27·45	24·95	22·95	20·84	0·629	0·826	0·600	0·393	0·139
12	27·10	29·21	25·30	22·45	19·22	0·653	0·838	0·600	0·404	0·134
13	27·33	30·85	25·95	22·00	17·36	0·596	0·814	0·602	0·403	0·115
14	28·18	32·30	25·52	21·31	15·66	0·606	0·816	0·576	0·411	0·124
15	28·48	33·61	25·37	20·23	13·86	0·607	0·832	0·576	0·400	0·119
16	23·64	26·90	24·41	22·56	19·82	0·497	0·798	0·585	0·421	0·161
17	25·15	27·28	24·00	21·62	17·82	0·639	0·795	0·574	0·408	0·127
18	25·60	28·15	23·99	21·06	16·35	0·641	0·787	0·570	0·413	0·141
19	25·85	29·45	24·22	20·57	14·53	0·618	0·781	0·568	0·414	0·138
20	25·11	29·44	23·67	19·72	13·04	0·604	0·781	0·568	0·417	0·140
21	23·87	26·68	24·25	22·49	19·90	0·517	0·779	0·572	0·417	0·170
22	24·05	27·68	24·55	22·32	18·90	0·521	0·781	0·576	0·424	0·173
23	25·62	28·30	24·52	21·81	17·60	0·611	0·773	0·569	0·417	0·160
24	25·80	29·03	24·40	21·15	15·94	0·613	0·772	0·571	0·425	0·167
25	26·29	29·67	24·32	20·60	14·52	0·619	0·763	0·564	0·419	0·158
26	25·76	27·92	25·26	23·48	20·76	0·590	0·781	0·569	0·422	0·177
27	25·46	28·16	24·89	22·59	19·13	0·581	0·771	0·569	0·421	0·173
28	24·90	28·20	24·33	21·66	17·52	0·563	0·756	0·556	0·411	0·163
29	25·89	28·69	24·18	20·99	16·01	0·619	0·759	0·563	0·419	0·170
30	26·10	29·36	24·16	20·51	14·72	0·619	0·759	0·565	0·422	0·173

convection. The vertical temperature gradient has been determined for two-dimensional flow in a vertical slot in the boundary-layer regime; Eckert and Carlson [6] have obtained a vertical temperature gradient of 0·6 for air and Elder [8] has found 0·50 for paraffin and 0·55 for silicone oil (100 cS).

CONCLUSIONS

Convection produced by the action of the centrifugal acceleration on a density gradient normal to it differs from natural convection driven by gravity for two reasons. First, the centrifugal acceleration is a strong function of radial position and secondly the Coriolis acceleration can play an important role in rotating convection (although it is not expected that it dominates the present problem). The Nusselt number depends on the imposed temperature difference to the 0·4 and 0·25 powers for the low and high Prandtl number silicone oils for the conditions of the experiments as compared to the 0·3 power obtained by Eckert and Carlson [6] for stationary natural convection under boundary-layer conditions using air. Furthermore, the Nusselt number depends on the 0·25 and 0·3 powers of the centrifugal acceleration evaluated at the outer edge of the cavity as compared to natural convection where the dependence on the acceleration of gravity is the same as the dependence on the imposed temperature difference. Thus the dependencies are somewhat different from those obtained in stationary convection.

The centerline temperature profile is similar to that obtained in natural convection. For the rotating cavity the dimensionless radial temperature profile is independent of both rotational rate and imposed temperature difference for the conditions of the experiments. Except near the center and outer edge of the channel the radial temperature gradient is constant and is equal to $-0·8$ and $-0·6$ for Prandtl numbers of 7 and 3000 respectively. The absolute value of this gradient is similar to the range in vertical temperature gradient of 0·5 to 0·6 found previously by others for stationary natural convection.

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ETUDE EXPERIMENTALE DE LA CONVECTION LIBRE DUE AUX FORCES CENTRIFUGES DANS UNE CAVITE RECTANGULAIRE

Résumé—La convection thermique provoquée par les forces centrifuges a été étudiée expérimentalement dans une cavité rectangulaire de longueur 27,94 cm, de hauteur 2,62 cm et de largeur 2,54 cm. La cavité était chauffée par le dessus et refroidie par le dessous et était en rotation autour d'un axe vertical passant par le centre de la cavité. La cavité était remplie d'huiles de silicone ayant des nombres de Prandtl égaux à 7 et 3000, et tournait à une vitesse pouvant atteindre 565 RPM.

Le nombre de Nusselt caractérisant le transfert de chaleur entre la paroi supérieure et la paroi inférieure a varié comme les puissances 0,4 et 0,25 de la différence de température imposée, respectivement pour les fluides à faible nombre de Prandtl et à fort nombre de Prandtl, et comme les puissances 0,25 et 0,3 de l'accélération centrifuge évaluée sur la paroi externe de la cavité. Un gradient de température adimensionnel sur le rayon central a été obtenu et trouvé indépendant à la fois de la vitesse de rotation et de la différence de température imposée.

EINE EXPERIMENTELLE UNTERSUCHUNG DER FREIEN KONVEKTION IN EINEM RECHTECKIGEN HOHLRAUM UNTER EINWIRKUNG VON ZENTRIFUGALKRÄFTEN

Zusammenfassung—Die durch Zentrifugalkräfte beeinflußte Konvektion in einem rechteckigen Hohlraum mit 27,94 cm Länge, 2,62 cm Höhe und 2,54 cm Breite wurde experimentell untersucht. Der Hohlraum wurde von oben beheizt und unten gekühlt. Er rotierte um eine senkrechte, durch seinen Mittelpunkt verlaufende Achse. Die maximale Umdrehungszahl betrug 565 Umdrehungen pro Minute. Der Hohlraum wurde mit Silikonölen gefüllt, deren Prandtl–Zahlen 7 und 3000 betragen. Bei der niedrigen Prandtl–Zahl änderte sich die Nusselt–Zahl der Wärmeübertragung von der oberen zur unteren Fläche mit der 0,4-ten Potenz der aufgeprägten Temperaturdifferenz, bei der hohen Prandtl–Zahl ergab sich eine Änderung mit der 0,25-ten Potenz. Die Abhängigkeit der Nusselt–Zahl von der an der äußeren Ecke des Hohlraums berechneten Zentrifugalbeschleunigung war bei der niedrigen Prandtl–Zahl durch die 0,25-te Potenz gegeben, bei der hohen Prandtl–Zahl durch die 0,3-te Potenz.

ЭКСПЕРИМЕНТАЛЬНОЕ ИЗУЧЕНИЕ СВОБОДНОЙ КОНВЕКЦИИ В ПРЯМОУГОЛЬНОЙ ПОЛОСТИ, ВЫЗВАННОЙ ЦЕНТРОБЕЖНЫМИ СИЛАМИ

Аннотация — Экспериментально изучался вызванная центробежными силами тепловая конвекция в прямоугольной полости длиной 27,94 см, высотой 2,62 см и шириной 2,54 см. Полость нагревалась сверху, охлаждалась снизу и вращалась вокруг вертикальной оси, проходящей через её центр. Полость заполнялась силиконовыми маслами с числами Прандтля 7 и 3000 и вращалась со скоростью до 565 об/мин. Число Нуссельта для переноса тепла от верхней поверхности полости к нижней изменялось пропорционально приложенной разности температур в степени 0,4 и 0,25 для жидкости соответственно с малыми и большими значениями числа Прандтля и пропорционально центробежному ускорению в степени 0,25 и 0,3, рассчитанному на внешней кромке полости. Получен безразмерный радиальный градиент осевой температуры и найдено, что он не зависит ни от скорости вращения, ни от приложенной разности температур.