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TURBULENT CONVECTIVE HEAT TRANSFER IN AN INCLINED TUBE WITH LIQUID SODIUM

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Turbulent convective heat transfer in a long closed cylindrical tube with $L \approx 20D$ ($D = 96$ mm is the diameter and L is the tube length) filled with liquid sodium, heated at one end face and cooled at the other, is studied experimentally for three different positions: vertical, inclined at 45 degrees to the vertical plane and horizontal. The Rayleigh number, which is determined by the superimposed temperature difference and tube diameter, varies within the range of $\mathrm{Ra} = (1-6)\cdot 10^6$. It is shown that convective heat transfer along the tube is most effective in the inclined tube, where intense large-scale circulation (LSC) exists against the background of developed small-scale turbulence. In the horizontal position, turbulence is weak, but the LSC provides moderate heat transfer. In the vertical tube, LSC is absent, turbulent fluctuations are most active, but heat transfer is the weakest. The dependence of the Nusselt number on the Rayleigh and Prandtl numbers in the form $\mathrm{Nu} \sim (\mathrm{Ra\,Pr})^x$ gives $x \approx 1$ for the horizontal tube and $x \approx 0.8$ for the vertical and inclined ones, which is essentially above the values known for turbulent convection in *short* vertical cylinders at "hard" ($x = 2/7$) and "ultrahard" ($x = 1/2$) convection.

Introduction. Interest to heat and mass transfer in liquid metals is largely stimulated by their application as coolants in nuclear reactors [1, 2], fusion reactors [3, 4] and space power plants [5]. In the design analysis of heat and mass transfer processes occurring in these systems at a shutdown of forced coolant circulation, the numerical codes must be verified by using experimental data on free convection of metal in long cylinders having different orientations with respect to gravity. Experimental data on free convection of liquid metals in cylinders with $L \gg D$ (L is the cylinder length, D is the diameter) are rare. Some studies have been made on Rayleigh–Bénard convection (relatively short vertical cylinders heated from the bottom), addressing the dependence of the dimensionless characteristic of convective heat transfer efficiency and the Nusselt number $\mathrm{Nu} = QL/\lambda\Delta T$ on the Rayleigh number defined for the Rayleigh–Bénard problem through the vertical scale $\mathrm{Ra}_L = g\beta\Delta T L^3/(\nu\chi)$. Here Q is the heat flux, λ is the thermal conductivity, ΔT is the temperature difference across the cell, β is the thermal expansion coefficient, ν is the viscosity, and χ is the thermal diffusivity. The convection of sodium in a set of vertical cylinders with $0.03 \le L/D \le 0.22$ has been investigated in [6]. Turbulent convection of mercury has been studied in a cylinder with $L = D$ [7]. Experiments with mercury in cylinders with $L = D$ and $L = 2D$ in [8] have revealed a power law $\mathrm{Nu} \sim \mathrm{Ra}^{2/7}$ in an extended range of the Rayleigh number $10^5 \le \mathrm{Ra}_L \le 10^{11}$. For comprehensive reviews on turbulent Rayleigh–Bénard convection, we refer to [9, 10].

The present study concerns a turbulent convective heat transfer at a low Prandtl number in *long* cylindrical cavities with different space orientation. Radial heat transfer in long tubes under forced circulation of mercury was studied experimentally for different configurations of the applied magnetic field in context

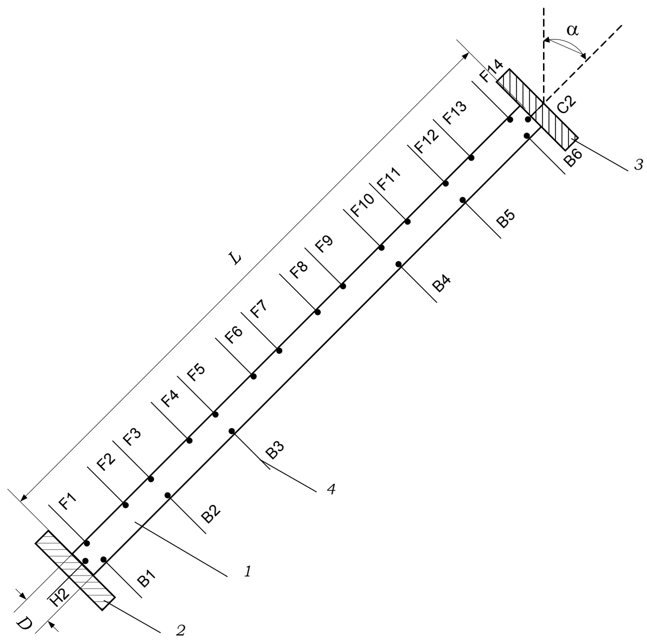

Fig. 1. Experimental setup.

of the problem of tokamak cooling systems [11, 12]. This paper presents results of an experimental study on free turbulent convection in liquid sodium (without pumping and magnetic field) in a cylindrical tube of the aspect ratio $L = 20.6D$, inclined to the vertical plane at an angle α. We consider $\alpha = 0$, 45 and 90 degrees.

1. Experimental setup. We study the convection of sodium in a cylindrical tube (*1*) (Fig. 1) of length $L = 1980$ mm and diameter $D = 96$ mm made of stainless steel (the wall thickness is 8 mm) closed by copper heat exchangers (at one end an electric heater and a cooler at the other). The cooper plates (*2*, *3*) of thickness 15 mm are in contact with the sodium. The cooler consists of a copper plate with 474 copper rods 200 mm long and 5 mm in diameter screwed into it. These rods are placed in a box and forcibly blown by the air with a controllable flow rate. The cavity has an expansion tank (not shown in Fig. 1). The cylinder and the expansion tank are fully insulated by mineral wool and aluminum foil (the averaged thickness of the wool is 30 mm). The cylinder is placed on a frame, on which it can be mounted at a given angle. For inclined and vertical positions, the heater is below the heat exchanger, i.e. we study the case of heating from below.

Chromel–alumel thermocouples with an isolated junction of 1 mm diameter are used for temperature measurements. The maximum sampling rate for each thermocouple is 75 Hz. The locations and numbering of 22 thermocouples (*4*) placed in the sodium through the tube wall are shown in Fig. 1. Thermocouples F1–F14 are located along the cylinder's generatrix at a distance of 10 mm from the wall so that even thermocouples as well as uneven thermocouples are located equidistant from each other. Sensors in the line F1-F14 are also used to measure the average axial velocity component in the area between adjacent thermocouples. This velocity is estimated from the position of the maximum of the cross-correlation function calculated for each pair of signals from adjacent sensors. Thermocouples B1–B6 are arranged symmetrically to F1, F3, F5, F10, F12 and F14, respectively.

Table 1. Main characteristics of all regimes studied.

n	α [deg]	ΔT [^{o}C]	$< T >$ [^{o}C]	T_{rms} [^{o}C]	Pr $\times 10^3$	Ra$_D$ $\times 10^{-6}$	Nu	Gr $\times 10^{-8}$	$< V >$ [cm/s]	Re $\times 10^{-3}$
1	0	40.1	135.6	0.98	9.3	2.3	9.3	2.5	-	-
2	0	50.0	144.7	1.31	9.0	3.0	11	3.3	-	-
3	0	50.6	144.6	1.36	9.1	3.0	11	3.3	-	-
4	0	60.4	137.7	1.64	9.2	3.5	13	3.8	-	-
5	0	72.8	150.4	2.00	8.9	4.4	15	4.9	-	-
6	0	82.9	158.4	2.29	8.7	5.2	17	5.9	-	-
7	45	33.4	135.5	0.89	9.3	1.9	71	2.1	4.3	6.7
8	45	45.5	150.1	1.21	8.9	2.8	93	3.1	5.7	9.3
9	45	51.1	182.0	1.49	8.0	3.5	102	4.3	5.7	10
10	45	52.9	177.3	1.48	8.1	3.5	104	4.3	5.9	10
11	45	54.8	168.0	1.52	8.4	3.5	108	4.2	6.0	10
12	45	55.3	167.6	1.70	8.4	3.6	108	4.2	6.0	10
13	45	56.0	165.7	1.71	8.5	3.6	108	4.2	6.0	10
14	45	58.6	155.9	1.71	8.7	3.6	112	4.1	6.0	9.9
15	90	25.6	142.7	0.10	9.1	1.5	27	1.6	2.0	3.2
16	90	44.0	143.0	0.14	9.1	2.6	48	2.8	3.0	4.8
17	90	52.8	145.0	0.18	9.0	3.1	57	3.5	3.2	5.1
18	90	64.5	148.3	0.18	8.9	3.9	71	4.3	3.7	6.0
19	90	70.3	166.8	0.17	8.4	4.5	79	5.3	4.0	6.8

This design allows the temperature of the heater and the air flow rate in the cooler to be maintained. Therefore, we achieve a steady convection regime (the characteristic time required is 2 hours), at which point the measurements are made. The temperature difference between the end heat exchangers reaches up to 80°C. The Rayleigh number is defined through the temperature drop along the cylinder ΔT and cylinder diameter $\mathrm{Ra}_D = g\beta\Delta T D^3/(\nu\chi)$. The characteristic temperature difference ΔT is taken to be equal to the temperature difference between the thermocouples H2 and C2, which are located in the sodium on the cylinder axis at 5 mm from the inner plates, respectively.

Note that in the Rayleigh–Bénard problem the conventional Rayleigh number is determined by the height of the cavity. In the case of vertical cylinder, the length L and the number Ra_L can be useful for comparison with the results obtained in vertical (mainly short) cylinders. However, in the case of horizontal tube, the number Ra_L is not an appropriate characteristic, giving a strong overestimation of Rayleigh numbers. Actually, we show below that turbulence in a horizontal tube is rather week, whereas Ra_L is of an order of 10^{10}. Thus we use Ra_D, minding that for our setup $\mathrm{Ra}_L/\mathrm{Ra}_D \approx 8700$.

2. Results. The characteristics of all 19 investigated regimes of convection are summarized in Table 1, which shows the tube inclination angle, the characteristic temperature difference, the mean temperature of the sodium in the cylinder, the r.m.s. of temperature fluctuations in the cavity central region, the average velocity in the section between F8 and F9, the Prandtl number $\mathrm{Pr} = \nu/\chi$ (for the mean sodium temperature through the cylinder), the Rayleigh number Ra_D, the Nusselt number $\mathrm{Nu} = (Q - Q_{\mathrm{loss}})L/\lambda\Delta T$ (Q is the heater power consumption for a given regime and Q_{loss} is the power required to maintain the same mean temperature of the sodium when the cooler is shut down), the Grashof number $\mathrm{Gr} = \mathrm{Ra}_D/\mathrm{Pr} = g\beta\Delta T D^3/\nu^2$, and the Reynolds number $\mathrm{Re} = VD/\nu$ defined

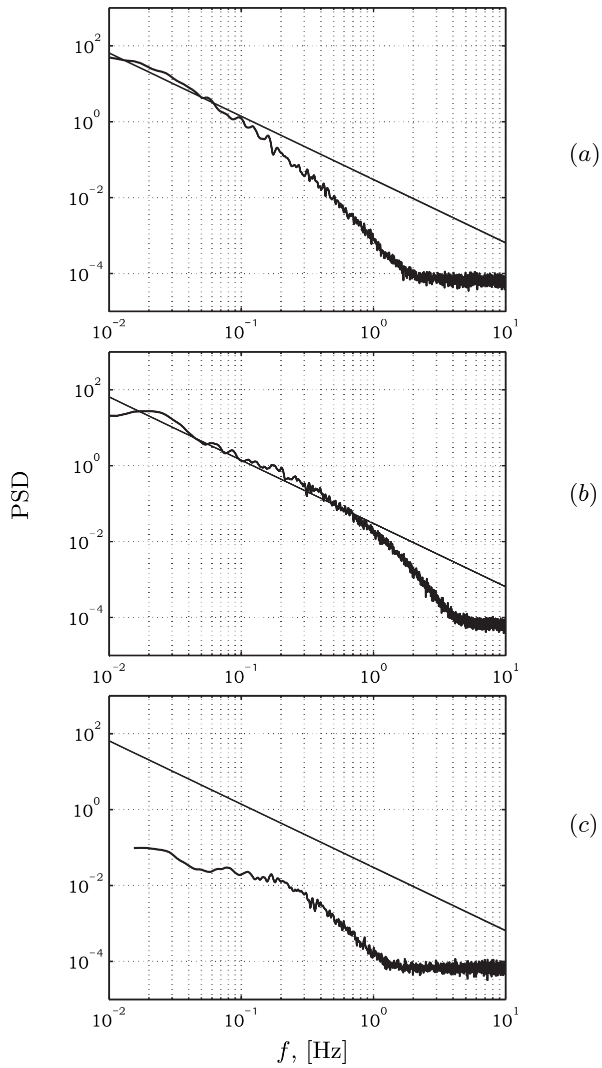

Fig. 2. Power spectral density of temperature fluctuations for thermocouple F8 in vertical (*a*), inclined (*b*), and in horizontal (*c*) tube. All spectra are given for $\mathrm{Ra}_D = 3.4 \cdot 10^6$. The solid line shows the slope "–5/3".

from the measured mean velocity V which characterizes the large-scale circulation (LSC).

The temperature fluctuations in sodium are weak, the r.m.s. values in the middle cross-section are $1.0-2.3$°C for a vertical tube, $0.9-1.7$°C for a tube inclined at 45 degrees and only $0.1-0.2$°C for a horizontal tube. The power spectral density (PSD) of the temperature fluctuations indicates a chaotic regime of convection. Fig. 2 shows the power spectral density of the temperature fluctuations in the central cross-section of the tube (for thermocouple F8) for regimes 4, 9, and 17, which are characterized by similar values of the Rayleigh number ($\mathrm{Ra}_D \approx 3.4 \cdot 10^6$).

The most developed turbulence was observed in the inclined channel, for which the spectrum includes a pronounced range with a power law similar to "–5/3". The analysis of cross-correlations indicated a stable LSC; the cross-correlation functions had a maximum (Fig. 3), the displacement of which can be used to determine the

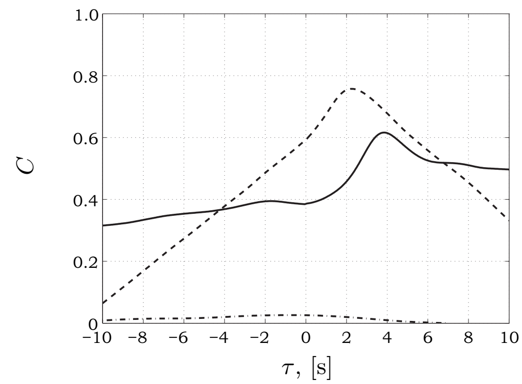

Fig. 3. Cross-correlation functions for temperature fluctuations at thermocouples F8 and F9 for vertical (dash-dotes), inclined (dashed line), and horizontal (solid line) tube.

mean flow rate. For the convection regimes under consideration, the mean velocity near the thermocouple F9 was 3–6 cm/sec.

The temperature pulsations in the vertical cylinder were slightly stronger than in the inclined one and the power law range was also observed in the spectral density of temperature fluctuations (Fig. 2*a*), although the low-frequency part of the spectrum showed a weakening of the pulsations. Analysis of cross-correlation functions for the temperature fluctuations at adjacent thermocouples revealed the absence of a stable large-scale circulation in the cylinder – the cross-correlation function had a diffused maximum near zero (Fig. 3).

The horizontal position of the tube alters the character of the temperature fluctuations qualitatively. The r.m.s. pulsations in the horizontal cylinder were lower than in the inclined one by an order of magnitude. There was no trace of developed turbulence in the spectrum (Fig. 2*c*). At the same time, the cross-correlation functions indicated a stable LSC, the rate of which was about half of that in the inclined cylinder.

An overview of effective heat transfer by a convective sodium flow in the cylinder in various positions is illustrated in Fig. 4, which shows the Nusselt numbers versus the Rayleigh numbers for all regimes studied. One can see that the most efficient heat transfer is in the inclined cylinder, in which both stable LSC and developed small-scale turbulence occur. The high level of small-scale turbulence was

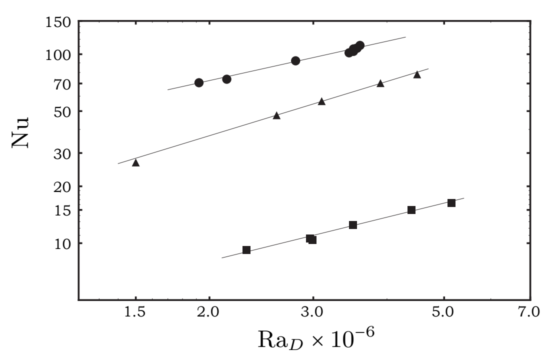

Fig. 4. The Nusselt number versus the Rayleigh number for vertical (squares), inclined (circles), and horizontal (triangles) tubes.

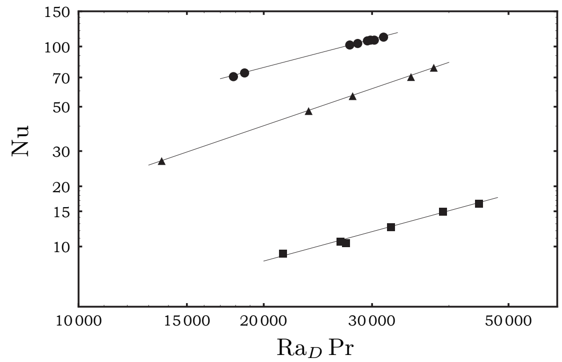

Fig. 5. The Nusselt number versus the product of the Rayleigh and Prandtl numbers for vertical (squares), inclined (circles), and horizontal (triangles) tube.

observed in the vertical cylinder, where the lowest values of the Nusselt number were observed (for $\mathrm{Ra}_D \approx 3.5 \cdot 10^6$, the Nusselt number for the vertical cylinder was about 13 if compared to about 100 for the inclined one). The Nusselt numbers for the horizontal cylinder are seen to be in an intermediate position in Fig. 4. It may be concluded that for integral heat transfer along the cylinder, the LSC is more important than the small-scale turbulence; the average large-scale flow persisting in the horizontal cylinder provides a sufficiently intense heat transfer in the absence of developed turbulence (for $\mathrm{Ra}_D = 3.1 \cdot 10^6$ the Nusselt number is equal to 57). Fitting the dependence Nu(Ra) by the power law, we get $\mathrm{Nu} \sim \mathrm{Ra}^{0.77}$ for the vertical, $\mathrm{Nu} \sim \mathrm{Ra}^{0.7}$ for the inclined, and $\mathrm{Nu} \sim \mathrm{Ra}^{0.95}$ for the horizontal tube.

However, the mean temperature for the sodium under different heating regimes was different (see Table 1), which means there was a change in Prandtl number. Therefore, it makes sense to write the Nusselt number as a function of the product of the Prandtl and Rayleigh numbers. The results are shown in Fig. 5. A power law fit can be done for all three tube's positions, and in all cases, the slope increases: $\mathrm{Nu} \sim (\mathrm{Ra\,Pr})^{0.84}$ for the vertical, $\mathrm{Nu} \sim (\mathrm{Ra\,Pr})^{0.8}$ for the inclined, and $\mathrm{Nu} \sim (\mathrm{Ra\,Pr})^{1.05}$ for the horizontal tube.

An important characteristic of the intensity of the global convective flow is the Reynolds number $\mathrm{Re} = VD/\nu$, which is defined through a characteristic velocity V of the LSC. For the characteristic velocity, we took the mean value of the axial

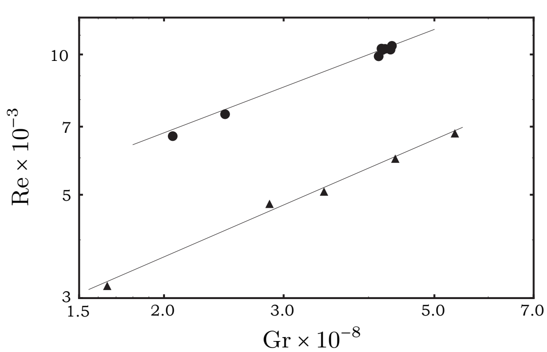

Fig. 6. The Reynolds number versus the Grashof number for inclined (circles) and horizontal (triangles) tube.

velocity calculated from the cross-correlation functions for the thermocouples F8 and F9. According to the values of the average velocity in the horizontal and inclined cylinders, the range of Reynolds numbers is $3000 < \mathrm{Re} < 10000$. In the vertical cylinder, the LSC vanishes and the Reynolds number cannot be defined.

Fig. 6 shows the dependence Re(Gr) for the inclined and horizontal cylinders in double logarithmic coordinates. Power fitting gives $\mathrm{Re} \sim \mathrm{Gr}^{0.63}$ for the horizontal and $\mathrm{Re} \sim \mathrm{Gr}^{0.56}$ for the inclined cylinders, i.e. the intensity of LSC grows a bit faster than the root square dependence.

3. Conclusions. The experimental studies on free convection of liquid sodium in a long tube ($L \approx 20D$) under a moderate Rayleigh number ($10^6 < \mathrm{Ra}_D < 6 \cdot 10^6$) have shown that the convective heat transfer there is mainly provided by the large-scale circulation of sodium and it is most effective in the inclined tube, where a strong LSC develops against the background of developed turbulence. In the horizontal tube, the LSC is less intensive, the flow can be characterized as transient to turbulent, and the Nusselt number is significantly lower. In the vertical tube, convective heat transfer is provided by turbulent mixing only (the large-scale circulation is absent, but the energy of turbulent fluctuations is maximum) and the Nusselt number has the lowest value (less by an order of magnitude than in case of the inclined tube).

In power laws for the Nusselt number of the form $\mathrm{Nu} \sim (\mathrm{Ra}\,\mathrm{Pr})^x$, the exponent has the maximum value for the horizontal tube ($x = 1.05$) and it is less and similar for the vertical ($x = 0.84$) and inclined ($x = 0.8$) tubes. The range of the considered Rayleigh numbers is below ten, thus the accuracy of the scaling exponents' estimation is low. However, the values obtained indicate that the value of the scale exponent is essentially above "2/7" confirmed for the short vertical cylinders [8] and even above "1/2" suggested for the "ultrahard" regime [7]. In the inclined and horizontal positions, the Reynolds number, which characterizes the intensity of LSC, has a power dependence on the Grashof number $\mathrm{Re} \sim \mathrm{Gr}^y$; for both positions, the dependence is slightly above the square root law: in the horizontal tube $y = 0.63$, and in the inclined tube $y = 0.56$.

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