TURBULENT CONVECTIVE HEAT TRANSFER IN A LONG CYLINDER WITH LIQUID SODIUM

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Abstract: Turbulent convection at low Prandtl numbers is studied experimentally. The experiments are performed in a cylindrical cell of large aspect ratio (H/D = 5) at different angles of inclination from vertical. The cell is filled with liquid sodium. The range of Rayleigh number is $3 \times 10^4 < Ra < 1.5 \times 10^5$. The averaged and spectral characteristics of temperature fluctuations are measured by thermocouple sensors and mean velocities are calculated using the cross-correlation analysis of these fluctuations.

1. Introduction

Experimental studies of sodium convection in cylindrical vessels are necessary to providing project calculations and verification of CFD codes on the example of a cylindrical cell (pipe section) and to better understanding turbulent convective processes occurring in the cooling circuits pipes of reactor facilities with sodium coolant. Currently available investigations devoted to the study of convection in fluids with small Prandtl number are performed on cells with aspect ratio of not greater than one [1-2]. In this paper we present results of an experimental study of convective flow of sodium in a relatively long cylindrical vessel in various positions (horizontal, inclined by 45°, vertical channel).

2. Experimental set-up

The experiments are carried out in a cylindrical container made of stainless still with an inside diameter of D = 0.168 m and a height of H = 0.850 m. Heating and cooling are produced by end heat exchangers. Hot heat exchanger consists of four closely adjacent to each other copper plates 15 mm in thickness. In directly adjacent to sodium cooper plate are drilled holes and turned channels for 5 thermocouples installation. Two of them are immersed in sodium at 5 and 1 mm for the boundary conditions measurements. Other 3 thermocouples are used for monitoring the radial uniformity of heating. The rest 3 copper plates have a cavity for placement of electric heating elements. The heater produces a maximum power of 6 kW. Cold heat exchanger is made of two copper plates of 15 mm thick. One of them, which directly adjacent to sodium, is identical to above-mentioned measuring plate and contains 5 thermocouples. In the second copper plate is turned channel for circulating cooling fluid. As the cooling fluid we use the mineral oil. A sketch of the experimental device is shown in Fig. 1 left. Additionally, the experimental setup includes the sodium storage system, the cell filling system, the frame to install the cylinder and lock it at predetermined angles, a set of sensors, the system for remote monitoring, the system for parameters of heating and cooling control, the system for measurements and acquisition of experimental data.

3. Measurement techniques. Cross-correlation method.

Measurements in sodium are performed using thermocouples made of the chromel-alumel thermocouple cable placed in a tube with an outer diameter of 1 mm. The space between the thermocouple and the tube wall is filled with mineral insulation, withstands temperatures up to 800 °C. Installation of thermocouples into the vessel is performed using an additional tube diameter of 3 mm and a length of 100 mm. It is welded to the channel, and then it is soldered thermocouple (Fig. 1 right). Data acquisition from each thermocouple is produced with a frequency up to 75 Hz.

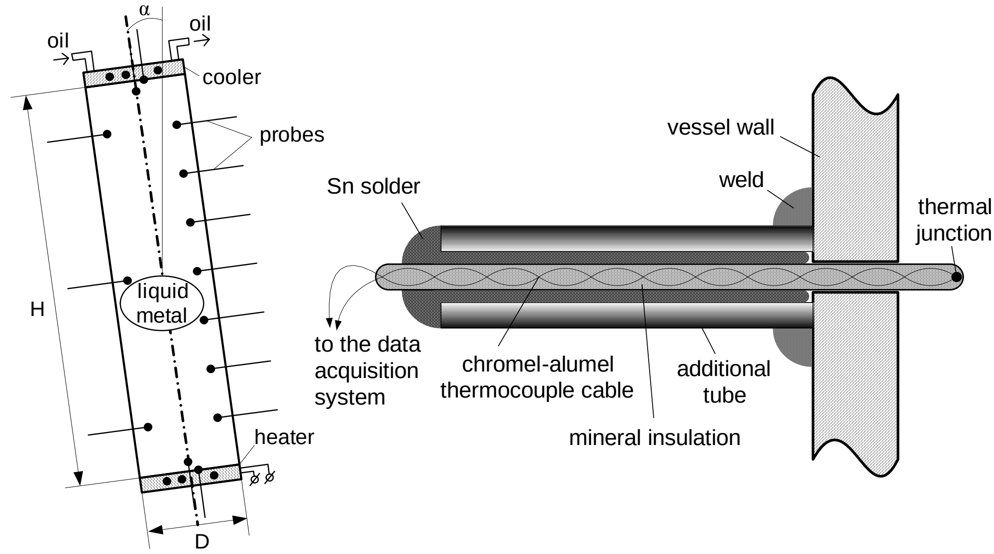

Figure 1: A sketch of the experimental cell (left); a scheme of thermocouple sensor (right).

Velocity measurements in liquid sodium are generally difficult to perform due to the opacity and aggressiveness of the melt at high temperature. However, it is possible to receive mean velocity values by calculating the cross-correlation of temperature fluctuations on the neighboring thermocouples. In case of a turbulent convection of the liquid medium there are overheated areas, which move together with the flow. Passing successively through two temperature sensors, such areas cause the bursts of temperature on these sensors with a certain time delay. Knowing the value of this delay and the distance between the sensors, the mean flow velocity in the space between these sensors can be defined. The maximum of cross-correlation function determines the mean time delay between the bursts on the neighboring sensors. In case of our experimental set-up, cross-correlation function is drawn for each pair of sensors in a line of thermocouples that allows us to get the velocity distribution along the cylinder (Fig. 2).

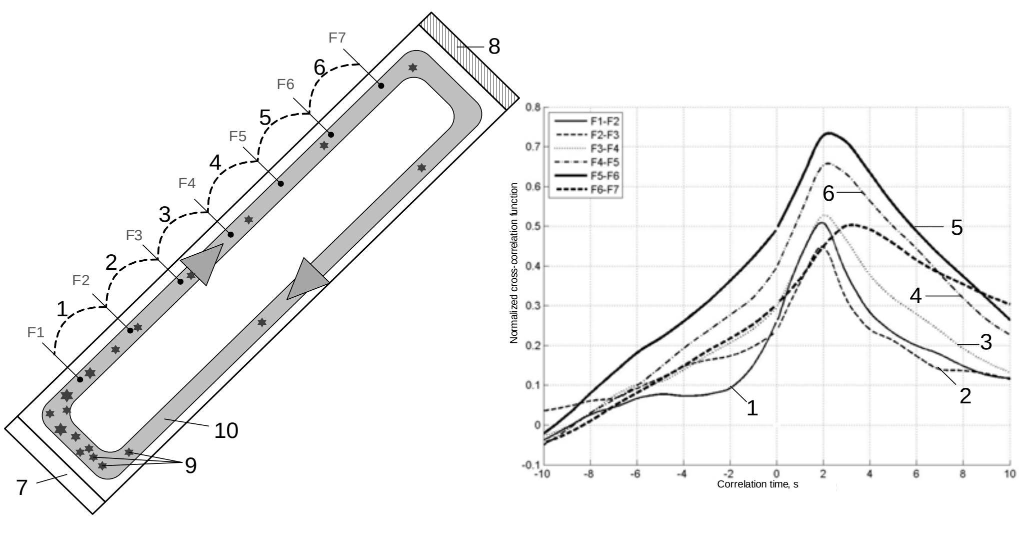

Figure 2: Velocity calculation for the inclined cylinder. 1-6 – on left: thermocouples pairs for which the cross-correlation function is drawn; on right: an example of functions obtained for these pairs; 7 – hot heat exchanger; 8 – cold heat exchanger; 9 – overheated areas; 10 – flow.

4. Results and discussions

Measurements are carried out in a stationary mode with a preset temperature of hot heat exchanger T_h. For each cylinder position from 5 to 7 experiments with different power of heating are conducted. Fig. 3 shows a scheme of a horizontal vessel applied with a time-averaged value of temperature minus the average temperature in the channel and the average velocity for T_h = 225°C.

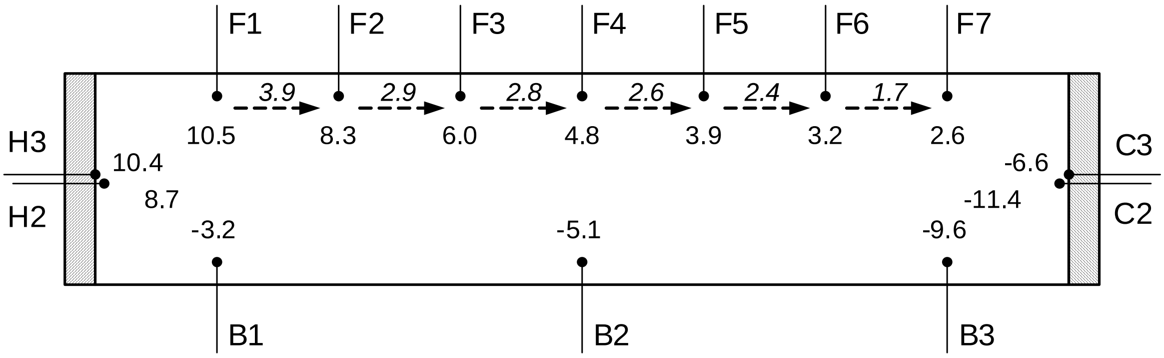

Figure 3: Horizontal vessel with applied experimental data. A dashed arrow with italic numbers shows direction and values of the average velocity.

At horizontal position of the cylinder experiments are carried out for Th = 175; 200; 225; 250; 275; 300; 325 °C which correspond to the Rayleigh number Ra = 0.49; 0.57; 0.67; 0.80; 0.93; 1.09; 1.27 * 10^5 calculated according to the formula:

$$Ra = \frac{g\beta\nabla T}{\nu\chi} r^4,$$

where r - radius of the cylinder, β - expansion coefficient, ν - kinematic viscosity, χ - thermal diffusivity, g - acceleration of gravity.

Velocity and temperature distribution along the cylinder are shown in Fig. 4.

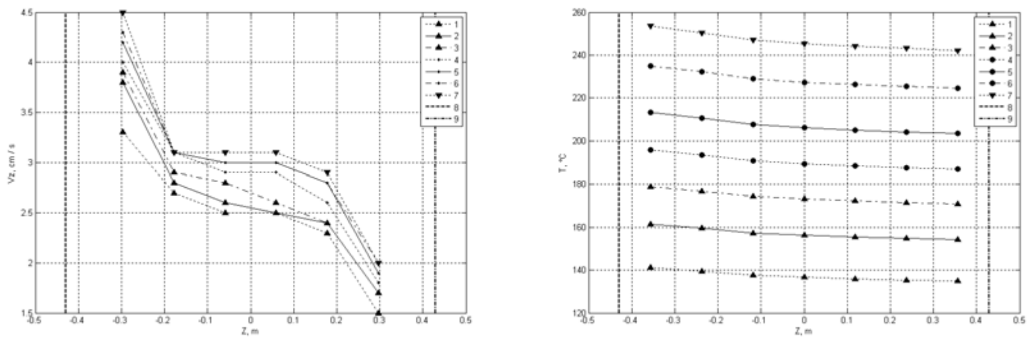

Figure 4: Velocity and temperature distribution along the horizontal cylinder. 1-7 correspond to different values of T_h.;8-9 correspond to Na-(heat exchanger) boundaries.

Fig. 5 shows a scheme of an inclined channel applied with the experimental data for T_h = 275°C. At such position of the cylinder experiments are carried out for Th = 175; 200; 225; 250; 275 °C which correspond to the Rayleigh number Ra = 0.34; 0.4; 0.45; 0.52; 0.63 * 10^5. Velocity and temperature distribution along the cylinder are shown in Fig. 5, right.

Fig. 6 left shows a scheme of a vertical channel applied with the experimental data for T_h = 175°C. Fig. 6 top right shows plots of cross-correlation functions. It can be seen that the maxima of the curves are poorly expressed and near zero in the time axis. This indicates that the amount of overheated areas that have passed through a pair of thermocouples in one and in the opposite direction is about the same. Thus, large-scale flow in the vertical cylinder cannot be registered.

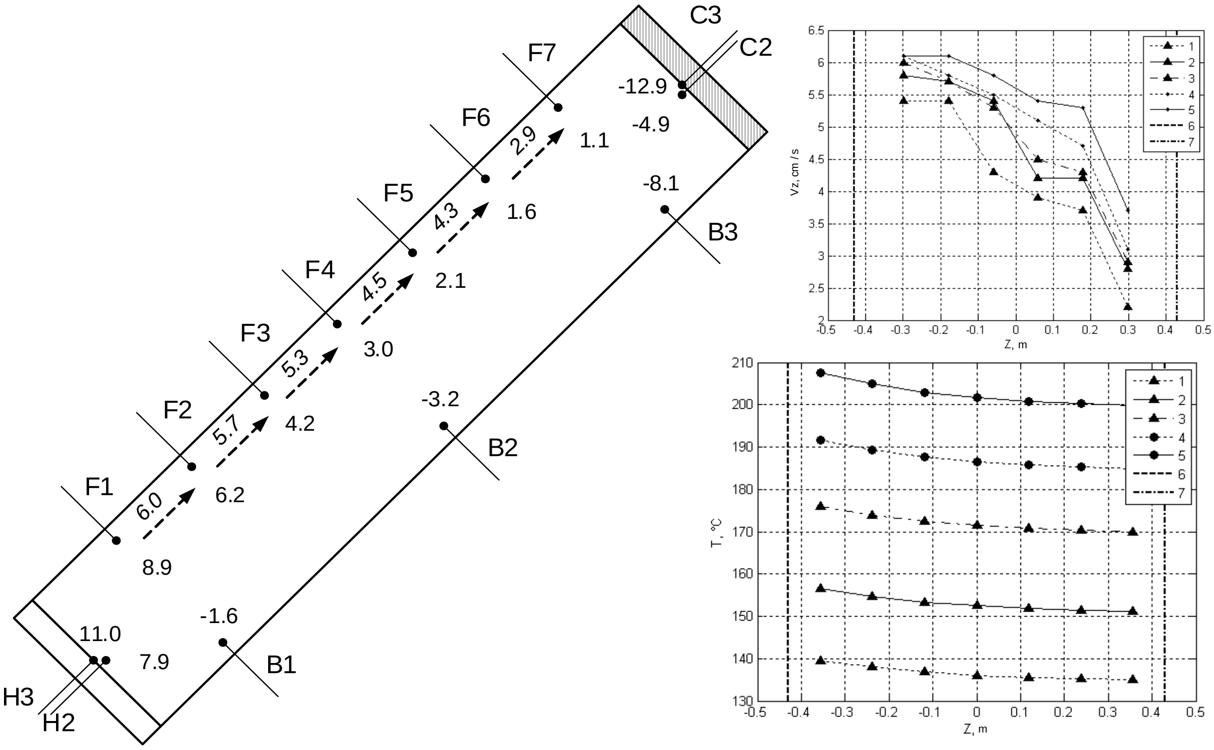

Figure 5: Inclined vessel with applied experimental data (left). Velocity and temperature distribution along the cylinder (right). 1-5 correspond to different values of T_h. 6-7 correspond to Na-(heat exchanger) boundaries.

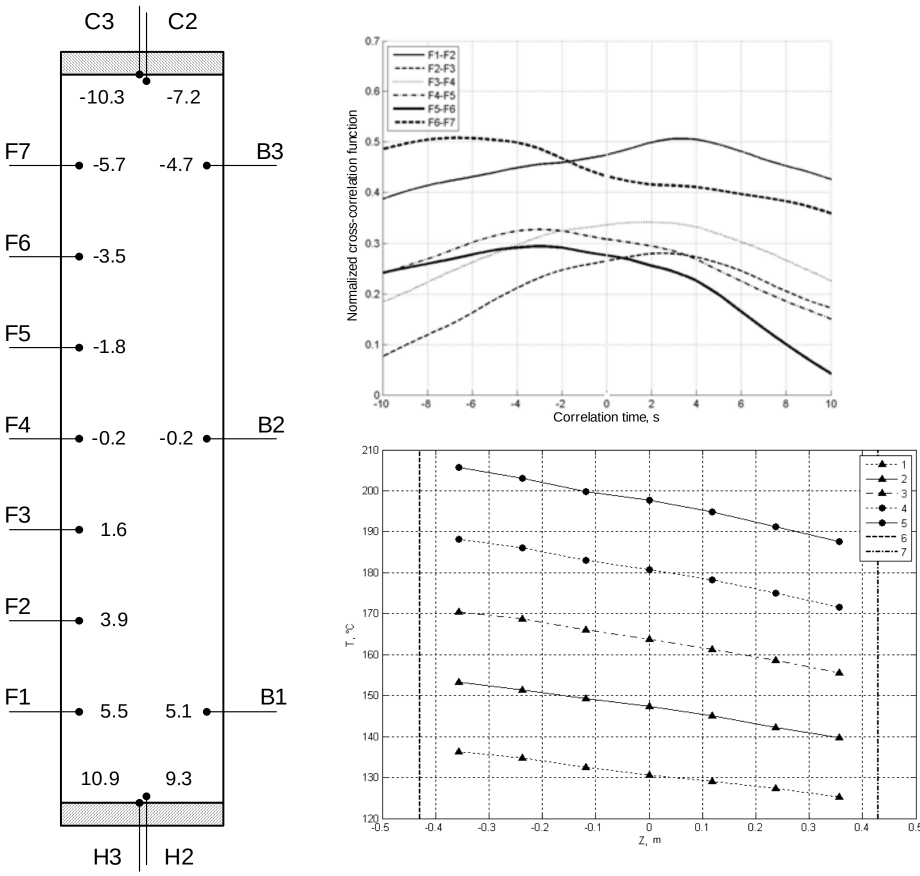

Figure 6: Vertical vessel with applied experimental data (left). Cross-correlation functions (top right); temperature distribution along the cylinder (bottom right). 1-5 correspond to different values of T_h. 6-7 correspond to Na-(heat exchanger) boundaries.

At vertical position of the cylinder experiments are carried out for Th = 175; 200; 225; 250; 275°C which correspond to the Rayleigh number Ra = 0.63; 0.77; 0.91; 1.05; 1.23 * 10^5.
Fig. 7 shows typical spectra of temperature fluctuations for thermocouples F1-F4 for all positions of the cylinder.

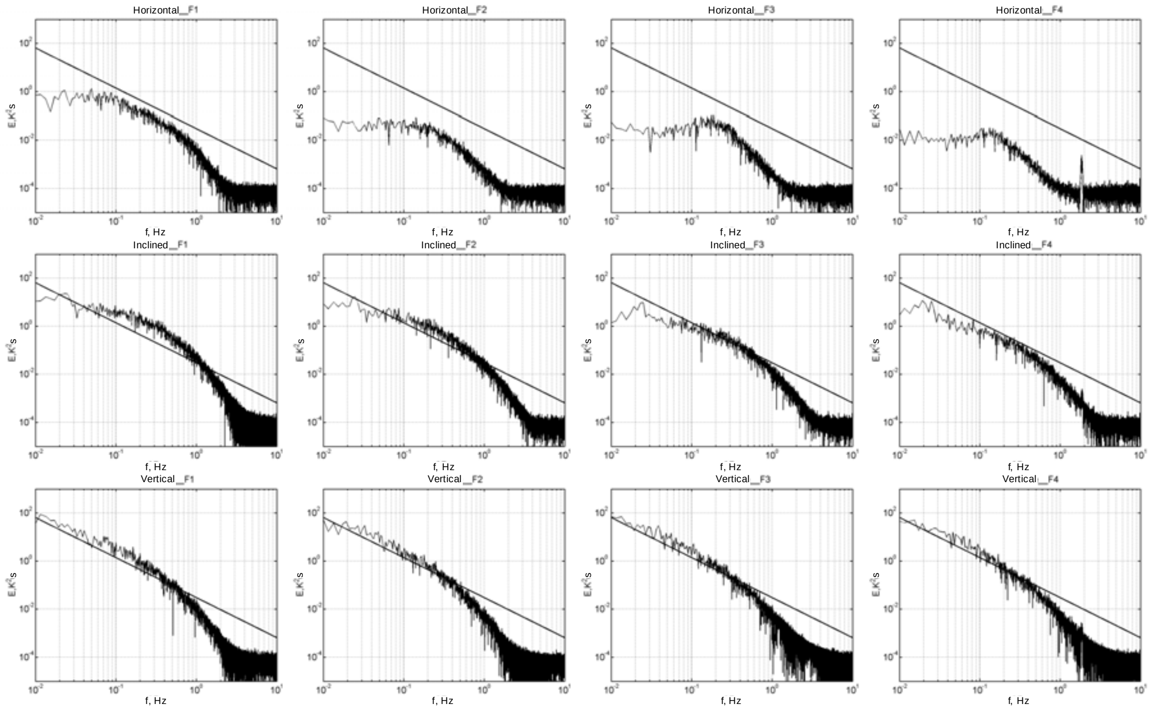

Figure 7: Typical spectra of temperature fluctuations for thermocouples F1-F4. From top to bottom - horizontal, inclined at 45° and vertical positions of the cylinder. Straight line – shows the Kolmogorov slope (-5/3).

For the case of a horizontal cylinder (top row in Fig. 7), it is obvious that form of the spectra changes along the cylinder from hot to cold heat exchanger - spectrum noticeably "sags", indicating a decrease in energy of turbulent fluctuations when approaching the cold heat exchanger. Moreover, there are obvious peaks at a frequency of about 0.15 Hz on the spectra of thermocouples F3 ÷ F5. Also, an inertial interval on the spectra of thermocouples F1 ÷ F3 exists.
In the case of cylinder inclined by 45° (middle row in Fig. 7), with removal from the hot heat exchanger spectra also "sags", but not so fast as in the case of the horizontal cylinder. At the same time on the spectra of all thermocouples inertial intervals are allocated.
In the case of a cylinder, vertically mounted, form of the spectra along the cylinder does not substantially changes. Thus on the spectra of all thermocouples inertial intervals are allocated.
Above-presented spectra indicate a turbulent nature of the convective flow in the cylinder at all considered conditions. The Reynolds number takes, however, a moderate value in the range varying from 3290 (minimum heat in horizontal cylinder) to 8050 (maximum heat in the inclined cylinder). Indeed, the spectra of the temperature fluctuations in the horizontal cylinder indicate that the inertial interval appear only in the area of average speed maximum values (in the floating up area near the hot heat exchanger and, apparently, floating down area near the cold heat exchanger.)

5. References

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[2] Horanyi S., Krebs L., Müller U. Turbulent Rayleigh-Bénard convection in low Prandtl-number fluids. Int. J. Heat Mass Transfer, vol. 42, p. 3983-4003, 1999.