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NATURAL CONVECTION HEAT TRANSFER PHENOMENA NEAR THE SURFACE COVERED BY RIBLETS

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Abstract. Natural convection experiments were conducted in water near the vertical cylindrical surface covered with a riblet film (V-grooves with the depth of 75 μm), with riblets oriented parallel and perpendicular to the flow (gravitation) direction. Experiments were performed in a range of modified Rayleigh numbers up to $1 \cdot 10^{14}$. Calorimetric measurements for estimating the heat transfer coefficients were supported by registering temperature fluctuations on the outer surface of the riblet film. The augmentation of the heat transfer of the micro-grooved surface was observed. However, no noticeable dependence of the heat transfer on the orientation of riblets was found. In the wall region, the well-ordered vortices were revealed for both parallel and perpendicular groove orientations and for the smooth surface. The frequency of temperature fluctuations depended on the Rayleigh number, and on the presence and orientation of riblets. The appearance of turbulence of higher intensity with parallel orientation of riblets was observed at the beginning of the transition regime. The dynamics of natural convective turbulence was higher than the heat transfer enhancement for the parallel groove orientation.

Key words: natural convection, surface with riblets, temperature fluctuations, heat transfer.

1. INTRODUCTION

Many investigations have focused on the effects of artificial wall roughness (riblets) on the heat and momentum transport. As a result, sufficient data on drag reduction, derived from the studies of riblet performance, are available. Other studies have covered forced flows and the effect of riblets on heat transfer as well as the effect of riblets on heat transfer at natural convection [1]. Riblets modify the structure of the boundary layer. Their height and shape (sharpness of their top) influence the stability of the viscous sublayer. This provides the frictional drag reduction of 5–9% within the limited Reynolds number interval [2] close to the optimal geometry of the riblets. As reported in [3], image techniques have revealed that the near-wall behaviour of turbulence at the wall, which is covered by riblets with streamwise oriented vortices, probably leads to drag reduction. The transition zone from a laminar to a turbulent flow regime begins at lower Reynolds (*Re*) and Rayleigh (*Ra*) numbers when the micro-grooved surfaces are used.

Wang et al. [4], who used air, reported that groove orientation has a slight effect on the results. Therefore, it was concluded that the augmentation of heat transfer is predominantly due to the increased surface area rather than to the flow structure.

This study focuses on the influence of riblets on the natural convective heat transfer from the vertical surface to the liquid. As is known, turbulence is the most important factor in the convective heat transfer. Due to this, it is rational to investigate the near-wall temperature fluctuations as the characteristics of the turbulence. It is not so clear at which value of *Ra* the real turbulent regime of heat transfer begins and how the transient region spreads. One of the characteristics of turbulence appearance may be the intensity of temperature pulsation. Due to this, the autocorrelation coefficients and the spectral density of temperature fluctuations were determined.

2. EXPERIMENTAL APPARATUS AND MEASUREMENTS

Distilled water was used as the working fluid. The test rig (Fig.1) consisted of a water-cooled water tank, in which the calorimetric tube (with an outer diameter of 16 mm) was located vertically. The calorimetric tube was made of copper. An electrical heater with potential wires to measure the voltage drop at the central isothermal part of the heater was located inside of the tube. To achieve a higher accuracy of calorimetric measurements, the filtered direct current supply of the heater was used.

To measure the difference of temperatures between the tube covered by the riblet film (3M Corporation PVC riblet film was used) and the liquid, six thermocouples were mounted in the grooves on the outer surface of the tube. The thermocouples were of one-wire copper-constantan-type (T-type, diameter of wire 100 μm).

Temperature differences were measured between the tube surface and the corresponding side location (level) of the ambient fluid in order to take into account the difference of ambient fluid temperature due to stratification effects in it. This mounting of thermocouples allows one to conduct direct measurements of the real temperature difference between water and tube surface.

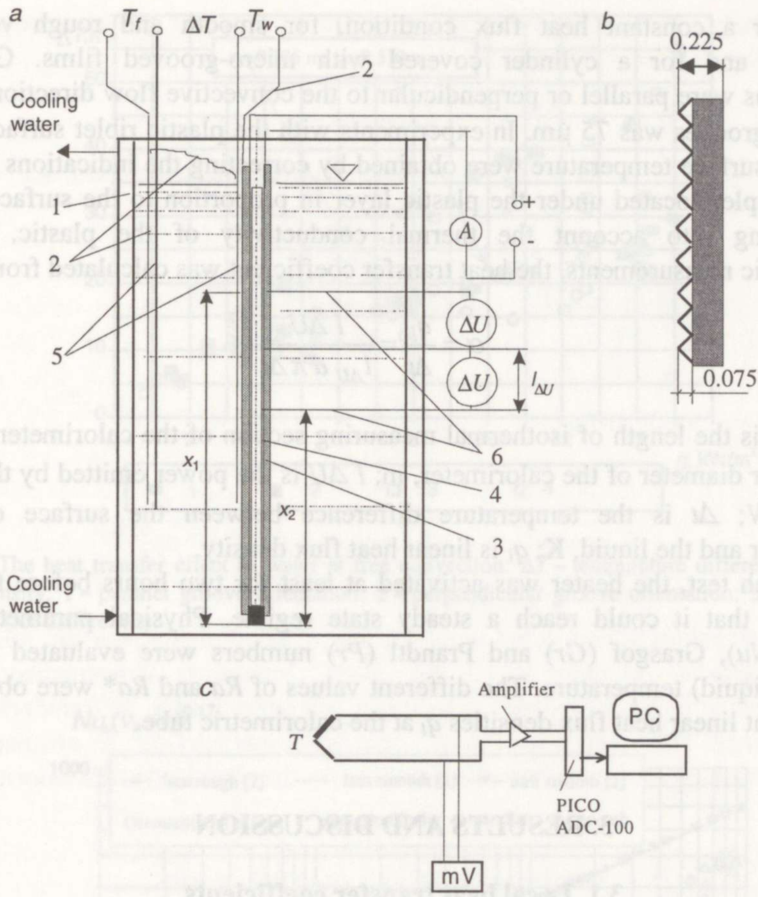

Fig. 1. The test rig for studying the free convection from the film surface covered by riblet in water: *a*) flow diagram of calorimetric measurements: 1 – water-cooled tank; 2 – thermocouple wires (copper); 3 – calorimetric tube; 4 – calorimetric heater; 5 – thermocouple wires (constantan); 6 – potential wires; the distances from the heated leading edge marked as $x_1 = 0.510$ m, $x_2 = 0.305$ m; *b*) dimensions of the riblet film (in mm); *c*) flow diagram of temperature fluctuations measurements.

The temperature-time correlation and spectral density measurements were made with T-type thermocouple probes (diameter of wires was 100 µm). The output signals were recorded in the digital form, using a high speed analogue-to-digital converter (PICO ADC-100, Pico Technology Ltd.) and the data acquisition interface (PicoLog, PicoScope) for a computer with a sampling rate up to 40 Hz. A linear amplifier, with the amplification coefficient of 1000, amplified the thermocouple signal before passing on to the analogue-to-digital converter (see Fig.1*c*).

Tests were conducted, using a filmless condition of the calorimeter as the baseline to be compared with theoretical correlation, with previous experimental results for a constant heat flux condition, for smooth and rough vertical cylinders, and for a cylinder covered with micro-grooved films. Groove orientations were parallel or perpendicular to the convective flow direction. The height of grooves was 75 μm. In experiments with the plastic riblet surface, the values of surface temperature were obtained by correcting the indications of the thermocouples located under the plastic layer in proportion to the surface heat flux, taking into account the thermal conductivity of the plastic. From calorimetric measurements, the heat transfer coefficient was calculated from

$$\alpha = \frac{q_l}{\Delta t} = \frac{I\,\Delta U}{l_{\Delta U}\, d\, \pi\, \Delta t}, \tag{1}$$

where $l_{\Delta U}$ is the length of isothermal measuring section of the calorimeter, m; d is the outer diameter of the calorimeter, m; $I\,\Delta U$ is the power emitted by the test section, W; Δt is the temperature difference between the surface of the calorimeter and the liquid, K; q_l is linear heat flux density.

For each test, the heater was activated at least for two hours before testing began, so that it could reach a steady state regime. Physical parameters in Nusselt (*Nu*), Grasgof (*Gr*) and Prandtl (*Pr*) numbers were evaluated at the ambient (liquid) temperature. The different values of *Ra* and *Ra** were obtained by different linear heat flux densities q_l at the calorimetric tube.

3. RESULTS AND DISCUSSION

3.1. Local heat transfer coefficients

To compare the results of experiments with different surfaces in water, first, the results were presented as the heat flux density dependence on the temperature difference between the calorimetric surface and the liquid (Fig. 2). It allows the comparison of the heat transfer effect in various situations at the calorimetric surface. Here the idea of Adiutory [5] was followed for heat transfer investigation and analysis. At the first step of the analysis of the results, the heat transfer coefficient was ignored.

Figure 2 shows that there are no noticeable differences in heat transfer depending on the orientation of riblets. However, there is a slight difference in heat transfer between a smooth surface and a surface covered by riblets.

Figure 3 shows the relations between $Nu_x\,(\nu_w/\nu_f)^{0.17}$ and Ra^* for water, where Nu_x is the local Nusselt number, $(\nu_w/\nu_f)^{0.17}$ is the correction factor of the influence of the variation of viscosity with temperature, Ra^* is the modified local Rayleigh number (Eq. (2)). The data for both parallel and perpendicular groove orientations and smooth surface are higher in the laminar region than the values calculated by Eqs. (3) and (4). Data for parallel and perpendicular groove

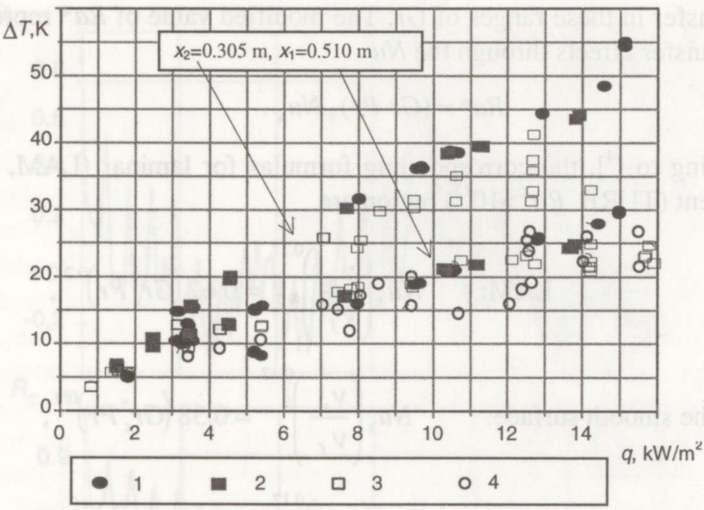

Fig. 2. The heat transfer effect in water at free convection: ΔT – temperature difference; q – heat flux density; 1 – parallel groove orientation; 2 – perpendicular groove orientation; 3, 4 – smooth surface (for different x).

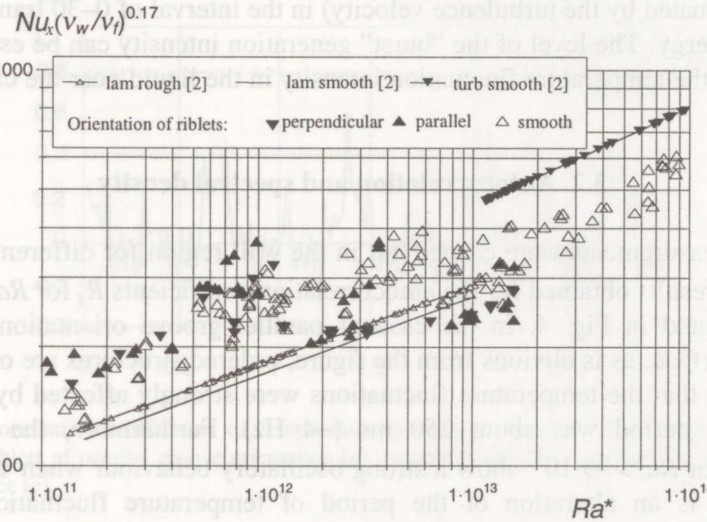

Fig. 3. Results of experiments on heat transfer coefficient at free convection.

orientations are close. The local Nusselt numbers for a smooth surface are lower than those for a rough surface. The results show that the surface with regular roughness and with different groove orientation provided insignificant changes in heat transfer in these ranges of Gr. The modified value of Ra^* represents also the heat transfer effects through the Nu

$$Ra^* = (Gr\,Pr)_x\,Nu_x\,. \tag{2}$$

According to [4], the corresponding formulas for laminar (LAM, $Ra^*<10^{13}$) and turbulent (TURB, $Ra^*>10^{13}$) region are

$$\text{LAM:} \qquad Nu_x\left(\frac{\nu_w}{\nu_f}\right)^{0.17} = 0.62\left(Gr_x^*\,Pr\right)^{0.2}, \tag{3}$$

$$\text{LAM for the smooth surface:} \qquad Nu_x\left(\frac{\nu_w}{\nu_f}\right)^{0.17} = 0.58\left(Gr_x^*\,Pr\right)^{0.2}, \tag{4}$$

$$\text{TURB:} \qquad Nu_x\left(\frac{\nu_w}{\nu_f}\right)^{0.17} = 0.22\left(Gr_x^*\,Pr\right)^{0.25}. \tag{5}$$

Energy transport is connected with the "burst" phenomena near the wall of a certain roughness. As noted in [3], the "burst" generation at normalized wall units (estimated by the turbulence velocity) in the interval of 0–30 transfers up to 80% of energy. The level of the "burst" generation intensity can be estimated by analyzing the temperature fluctuation intensity in the liquid near the calorimetric surface.

3.2. Autocorrelation and spectral density

The measurements were carried out in the wall region for different values of Ra^*. The results obtained for the autocorrelation coefficients R_τ for $Ra^* = 1\cdot 10^{13}$ are illustrated in Fig. 4. In the case of parallel groove orientation and with smooth surface, as is obvious from the figure, ordered structures are observed. It was found that the temperature fluctuations were strongly affected by Ra^*. The oscillation period was about 250 ms (~4 Hz). Furthermore, the curves of $R_\tau = f(\tau)$ for $Ra^*>\sim 9\cdot 10^{12}$ show a strong oscillatory behaviour when τ increases, and there is an alteration of the period of temperature fluctuation as Ra^* increases. For equal values of Ra^*, the autocorrelation coefficients R_τ for the surface with perpendicular groove orientation at $Ra^*<\sim 7\cdot 10^{12}$ are in good agreement (by the time-scale) with parallel groove orientation and smooth surface. However, when $Ra^*>\sim 7\cdot 10^{12}$, the autocorrelation coefficients R_τ for the surface with perpendicular groove orientation decrease monotonously from unity at $\tau = 0$ and the periodicity is lost. A strongly periodic phenomenon of temperature fluctuations was obtained by Cheesewright and Doant [6] in the transient region of natural convection.

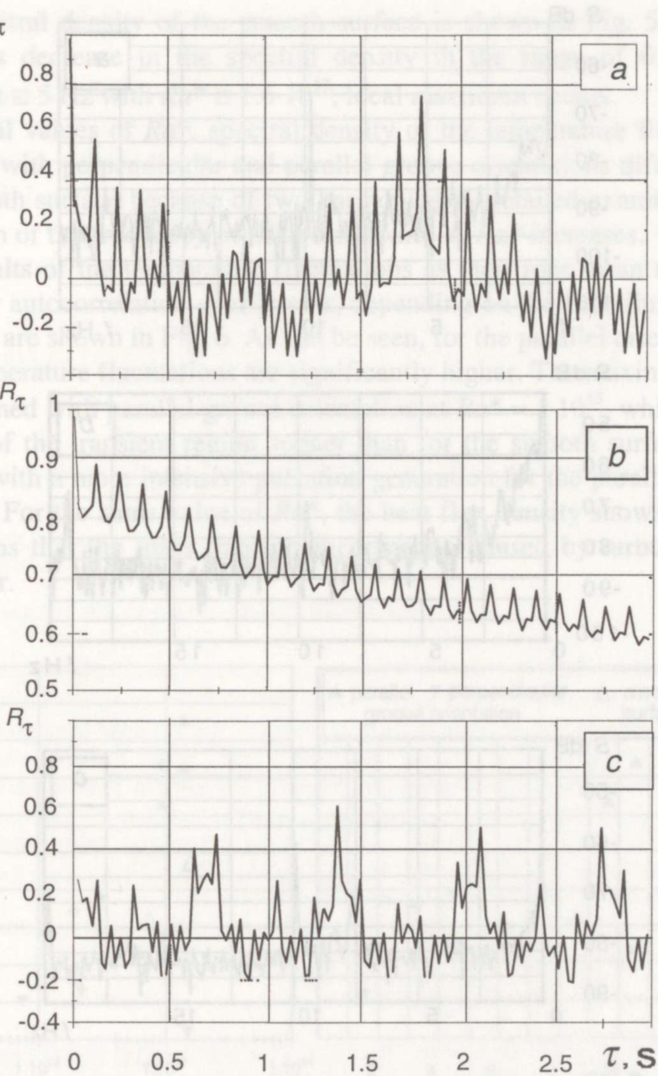

Fig. 4. Autocorrelation coefficients of temperature fluctuations at $Ra^* = 1{\cdot}10^{13}$ for the surface covered by riblets of parallel groove orientation (*a*), perpendicular groove orientation (*b*) and for a smooth surface (*c*).

As a result of the investigation, we obtained the spectral density of temperature fluctuation on a smooth surface and on that covered by riblets with perpendicular and parallel groove orientation (see Figs. 5*c* and *d*). At first, the test under the adiabatic ($q = 0$) condition provided a basis (Fig. 5*a*). It must be pointed out here that different values of Ra^* were obtained by changing the heat flux density q.

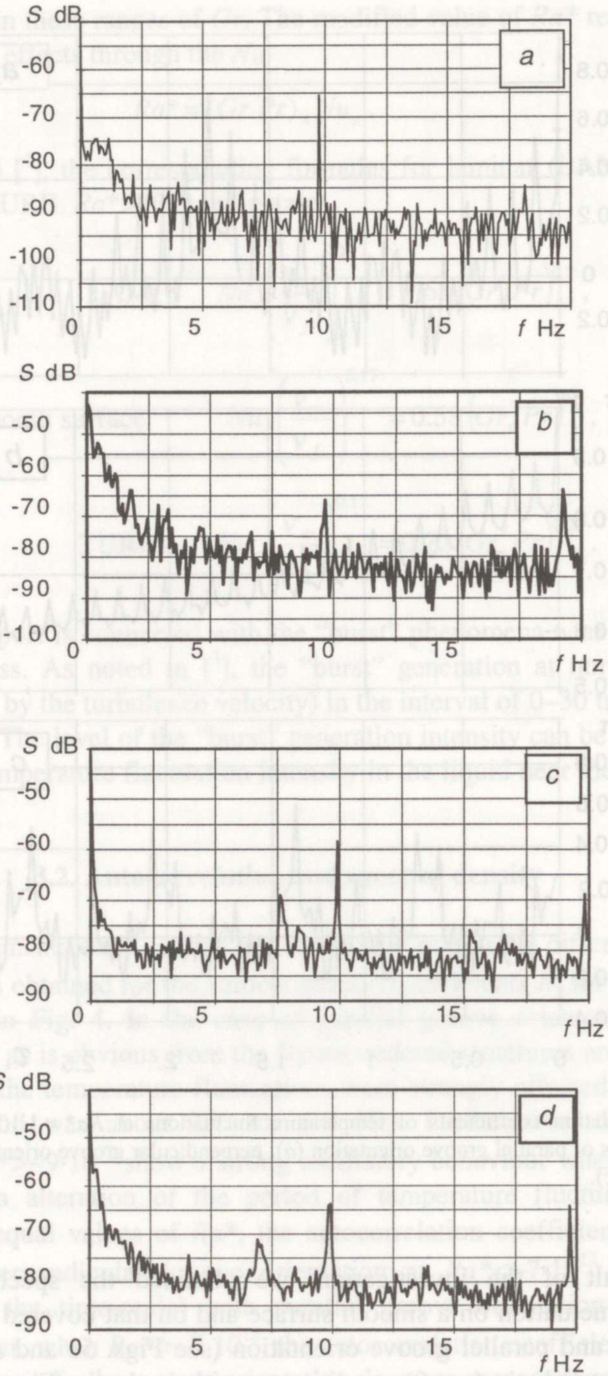

Fig. 5. Spectral density of temperature fluctuations on the smooth adiabatic ($q = 0$) surface (a), smooth surface (b), with perpendicular (c) and parallel (d) groove orientation of riblets at $Ra^* = 1{\cdot}10^{13}$.

The spectral density of the smooth surface is shown in Fig. 5*a*. There is a monotonous decrease in the spectral density in the range of 0.5 to 20 Hz. However, at $\cong$ 5 Hz with $Ra^* \cong 1.6 \cdot 10^{13}$, local maximum occurs.

For equal values of Ra^*, spectral density of the temperature fluctuations on the surface with perpendicular and parallel groove orientations differs from that of the smooth surface because of two harmonics. A detailed examination shows an alteration of the frequency of these harmonics as Ra^* increases.

The results of the temperature fluctuations as their root mean square values (R_t) of their autocorrelation coefficients, depending on the heat flux density and on the Ra^*, are shown in Fig. 6. As can be seen, for the parallel orientation of the riblets, temperature fluctuations are significantly higher. The maximum values of R_t are obtained with parallel groove orientation at $Ra^* = 1 \cdot 10^{13}$, which shows the beginning of the transient region sooner than for the smooth surface. It is also connected with a more intensive pulsation generation for the parallel orientation of grooves. For the same value of Ra^*, the heat flux density shows high values, which means that the mass transfer phenomenon caused by turbulence affects heat transfer.

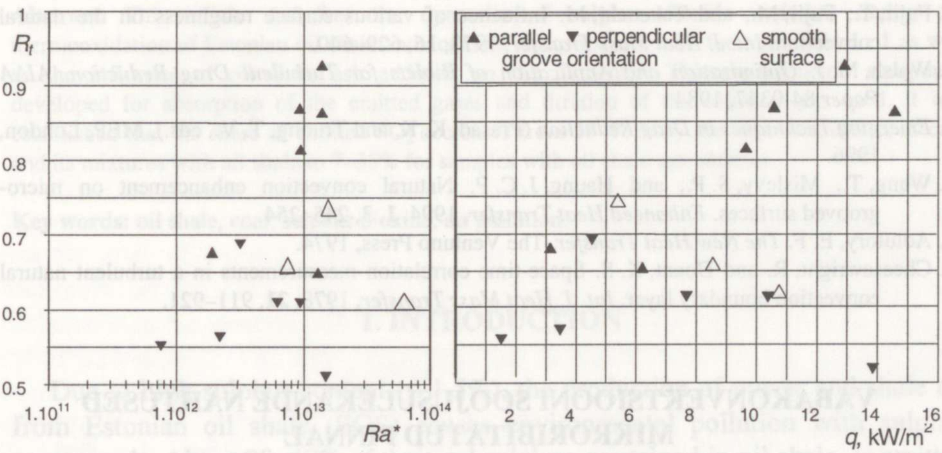

Fig. 6. The dependence of temperature fluctuations intensity on Ra^* and on the heat flux density q.

4. CONCLUSIONS

The present paper has analyzed the augmentation of heat transfer from the micro-grooved surface to water. No noticeable differences in heat transfer, depending on the orientation of riblets, were revealed.

Well-ordered structures in the wall region were found for both parallel and perpendicular groove orientations of the riblets as well as for the smooth surface.

The frequency of temperature fluctuations changed with the changes of Ra^* and with alternative orientation of riblets or lack of these.

The highest values of autocorrelation coefficients of the temperature fluctuations were obtained with parallel groove orientation at the transient region. In other words, the growth of fluctuation intensity shows that the transient region of the free convection flow has been reached, and that it begins sooner than for a smooth surface.

When using surfaces covered by riblets, forced convection tests may reveal the real effect of heat transfer augmentation.

ACKNOWLEDGEMENT

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VABAKONVEKTSIOONI SOOJUSÜLEKANDE NÄHTUSED MIKRORIBITATUD PINNAL

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On vaadeldud mikroribitusega kaetud vertikaalse silindri pinnal toimuvaid vabakonvektsiooni soojusülekande nähtusi vees. Eksperimentides on kasutatud firma 3M mikroribitusega plastikut ribi kõrgusega 75 µm. Statsionaarne kalorimeetriline mõõtmine näitas, et vabakonvektsiooni soojusülekandetegur ribitatud pinnalt vette on suurem kui siledalt pinnalt, kuid otsest sõltuvust ribituse orientatsioonist ei ole märgata. Samas on fikseeritud temperatuuripulsatsioonide intensiivsuse maksimum pikiribituse puhul üleminekupiirkonnas (modifitseeritud Ra^* järgi). Uuringu tulemusel võib väita, et mikrokaredus avaldab vabakonvektiivsele turbulentsusele suuremat mõju kui soojusülekandele.