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Application of infrared thermography for investigation of unsteady flow in a circular pipe

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Abstract:

The heat transfer of pulsating flow in pipes has been theoretically and experimentally investigated. The interest in this problem is due to increase in heat exchange efficiency. An experimental set-up has been constructed for the investigation of unsteady flow in a circular pipe. For the evaluation of convective heat transfer in pulsating flow the temperature of the pipe wall has been measured by IR- thermography.

1. Introduction

The heat transfer problem of pulsating flow in pipes and ducts has been considered in several publications [1-6]. The interest in this problem is due to possible applications, mainly in industry, to increase heat exchange efficiency.

The heat transfer of developing pulsatile laminar flow in duct was studied in [1]. The dependence of heat transfer on pulsation frequency at uniform wall temperature and constant heat flux at the wall was demonstrated.

The results of numerical studies on heat transfer characteristics of pulsating flow in a pipe with uniform temperature at the wall are given in [2,3].

The problem of pulsating laminar flow in a pipe with constant heat flux at the wall, when temperature becomes a linear function of downstream direction, was considered in [4].

The available experimental results about heat transfer in pulsating flow are inconclusive and contradictory [5-7].

The IR-thermography technique can be used in experimental research of heat transfer of pulsating processes [8,9]. The use of IR-thermography in unsteady accelerating flows is demonstrated in [10].

This paper is presenting a collection of some experimental results obtained with IR-thermography technique and thermocouples.

2. Experimental set-up

The experiments were made at Tallinn Technical University. The measurements were conducted on an experimental set-up, the scheme of which is given in Fig. 1. The main parts of the set-up are: 1 – pressure tank (~600 litres); 2 – test pipe (l = 2276 mm, d_{in} = 20 mm); 3 – insulated heating pipe (d = 100 mm); 4 – IR-camera; 5 – inductive flowmeter (feed frequency 500 Hz); 6 – pulsating flow generator (magnetic valve); 7 – expansion tank; 8 – circulation pump (Grundfos UPS-25-80); 9 – electric boiler TK-STLj (20 kW); 10 – heat meter (Landis & Gyr); 11 – thermocouples; 12 – manometer; 13 – pressure transducer (PTX 1400). The experimental set-up gives us the possibility to conduct research with pulsating frequencies up to 10 Hz. The system for recording measurements was prepared based on PC. Eight measured values can be recorded simultaneously. The temperature field fixed by IR-camera is syncronised by other measured physical values. The IR-camera used for the measurements was the Inframetrics Model 740 IR Imaging Radiometer sensitive in the 8-12 μm band. The temperature changes on the pipe wall resulting from

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the cooling effect of the flowing water are relatively low. In order to achieve higher accuracy of the effects of convective heat transfer in the flow, the measurement range of the IR-camera was set to 2º C, the smallest possible measurement range of the camera.

3. Theoretical analysis

Let us first use a simple mathematical model to study the problem in order to have some preliminary overview of the expected experimental results.

We use the slug-flow assumption that the velocity of the flow at every moment of time is constant in any cross-section of the tube, equalling the average flow velocity. Then the problem of the pulsating flow with constant heat flux at the wall is governed by the energy equation

$$\frac{\partial\theta}{\partial\tau}+v_m(1+\varepsilon\sin\omega\tau)\frac{\partial\theta}{\partial\xi}=\frac{\partial^2\theta}{\partial\eta^2}+\frac{1}{\eta}\frac{\partial\theta}{\partial\eta} \qquad (1)$$

and boundary conditions

$$\frac{\partial\theta}{\partial\eta}(\xi,1,\tau)=1,\ \ \theta(0,\eta,\tau)=0,\ \ \frac{\partial\theta}{\partial\eta}(\xi,0,\tau)=0. \qquad (2)$$

Here

$$\theta=\frac{T-T_0}{q_w r_0/k},\ \ v=\frac{u}{u_0},\ \xi=\frac{x}{r_0\mathrm{Pr},\mathrm{Re}},\ \ \eta=\frac{r}{r_0},\ \ \tau=\frac{tk}{\rho c_p {r_0}^2},$$

$$\mathrm{Pr}=\frac{\mu c_p}{k},\ \ \mathrm{Re}=\frac{\rho u_0 r_0}{\mu}, \qquad (3)$$

where T is temperature, u is fluid velocity in the axial direction, c_p, k, ρ are specific heat, thermal conductivity and density of the fluid, respectively, x, r are axial and radial coordinates within the tube, t is time, T_0 is the uniform temperature of the fluid when entering the region, where the heat flux at the tube wall q_w is given, r_0 is the radius of the tube, u_0 is constant reference velocity, μ is viscosity and Pr, Re are the Prandtl and Reynolds numbers, respectively.

From Eqs. (1) and (2) we obtain for mean temperature

$$\frac{\partial\bar{\theta}}{\partial\tau}+v_m(1+\varepsilon\sin\omega\tau)\frac{\partial\bar{\theta}}{\partial\xi}=2, \qquad (4)$$

where

$$\bar{\theta}=2\int_0^1\theta\eta d\eta. \qquad (5)$$

The solution of Eq. (4) for small values of ε can be written as

http://dx.doi.org/10.21611/qirt.2002.012

$$\overline{\theta} = 2\left\{\xi^{*} + \frac{1}{\omega}\left[-\varepsilon + \varepsilon^{2}\sin\omega\left(\tau - \xi^{*}\right)\right]\cdot\left[\cos\omega\left(\tau - \xi^{*}\right) - \cos\omega\tau\right]\right\}, \tag{6}$$

where $\xi^{*} = \frac{\xi}{v_m}$.

If we assume that the change of temperature in a cross section of the pipe is quasi-steady, then from Eqs. (1) and (6) we obtain for the temperature at the wall of the pipe

$$\theta_w = \overline{\theta} + \frac{1}{8}F\left(\xi^{*}, \tau\right). \tag{7}$$

where

$$\begin{aligned} F\left(\xi^{*}, \tau\right) = {} & 2\left(1 + \varepsilon\sin\omega\tau\right)\cdot \\ & \cdot\left[1 - \varepsilon\sin\omega\left(\tau - \xi^{*}\right) - \varepsilon^{2}\cos2\omega\left(\tau - \xi^{*}\right) + \varepsilon^{2}\cos\omega\left(\tau - \xi^{*}\right)\cos\omega\tau\right]. \end{aligned} \tag{8}$$

Fig. 2: shows the wall and mean temperatures calculated from Eqs. (6) and (7). For consideration of the real conditions of the experiment at the point of measurement with IR-camera the heat exchange on the wall of the pipe in Eq. (7) is divided by 100.

4. Experimental results

The scheme of experimental set-up is given in Fig. 1. The temperature of water heated by the electric boiler was in experiments 70˚ C and the temperature of cold water from the pressure tank was 18˚ C. Water pressure in the pressure tank was kept constant by regulating the pump speed. The mean flow pulsations in experiments were in the range 0.15…7.00 Hz.

Some experimental results corresponding to the pulsation frequency 0.9 Hz are presented in Fig. 3. In Fig. 4 calculated spectral energy density of the temperature measured by IR-camera and thermocouple, pressure and flow rate are given for the same experiment (Fig 3). Fig. 5 shows the maximums of spectral energy density, corresponding to temperature changes of pipe walls measured by IR-camera at different frequencies of flow rate pulsation.

The spectral energy density calculated from the results of experiments allow to conclude that the IR-camera is monitoring the changes in wall temperature, caused by pulsating flow, at least up to 5 Hz.

5. Conclusions

The pulsating flow in a pipe with constant heat flux at the wall was studied experimentally and with a simple mathematical model. The IR – thermography technique and thermocouples are used to determine the temperature at the wall of the pipe and in the flow. The temporal averages of these temperatures give changes in the Nusselt number. It makes possible to determine the effect of pulsation on the rate of heat transfer. The spectral energy density allows to conclude that the IR-camera is monitoring the changes in wall temperature, caused by pulsating flow, at least up to 5 Hz.

6. Acknowledgements

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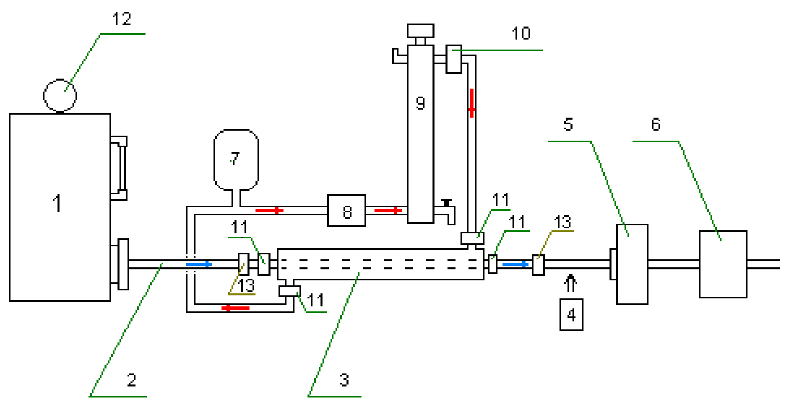

Fig. 1. *Experimental Set-up*

http://dx.doi.org/10.21611/qirt.2002.012

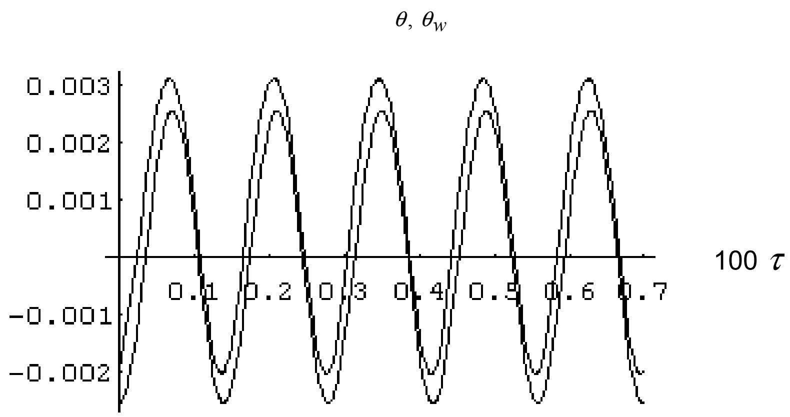

Fig. 2. *Calculated temperature at the wall of the pipe and the mean temperature vs. time for* ω *=4500,* ξ^* *=0.0007,* ε *=0.3*

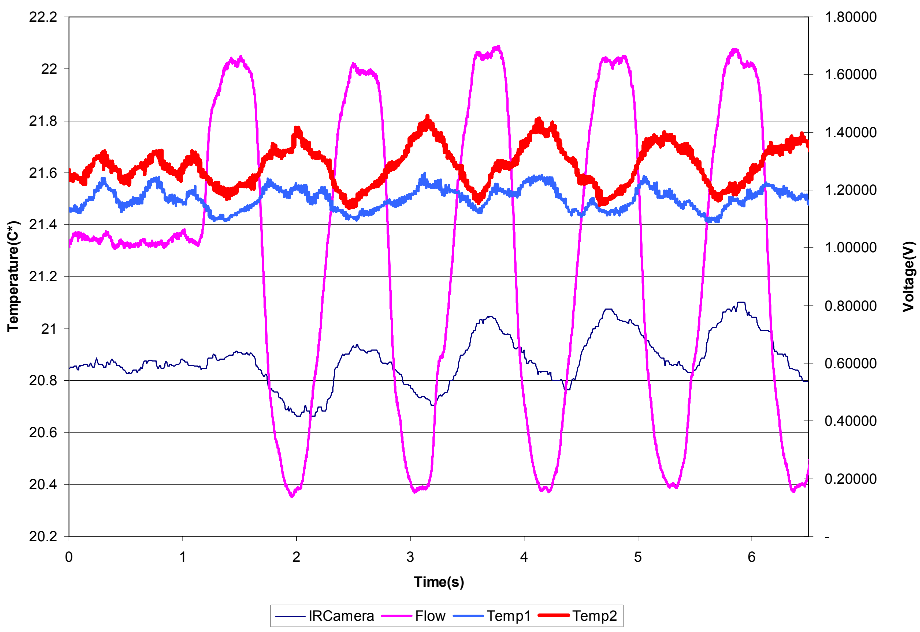

Fig. 3. *Recorded experimental results, flow pulsation frequency 0.9 Hz*

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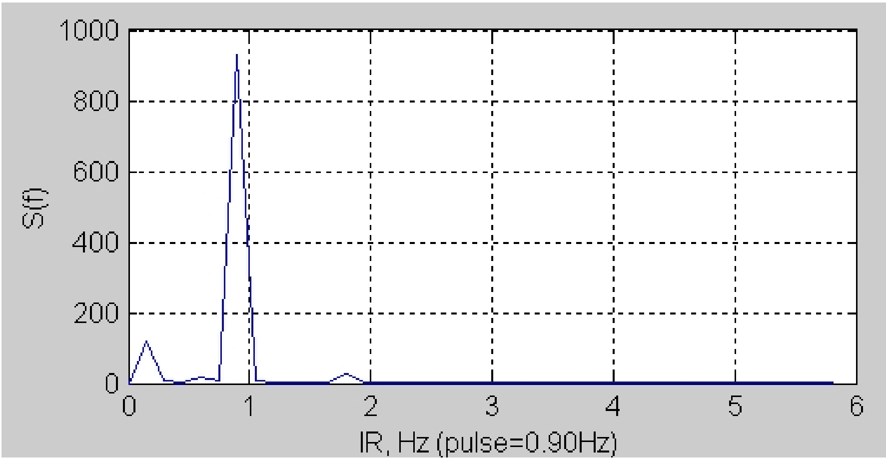

Fig. 4. *Spectral energy density*

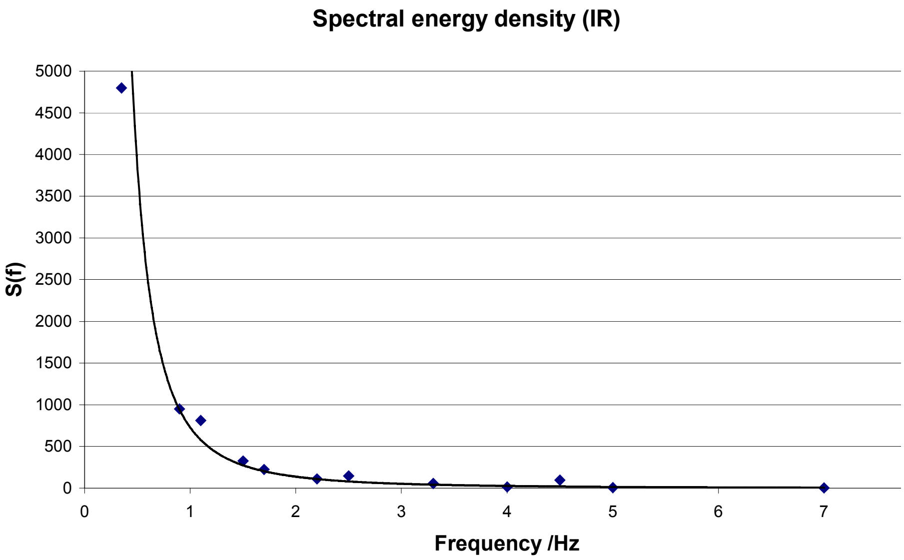

Fig. 5. *The maximums of spectral energy density*