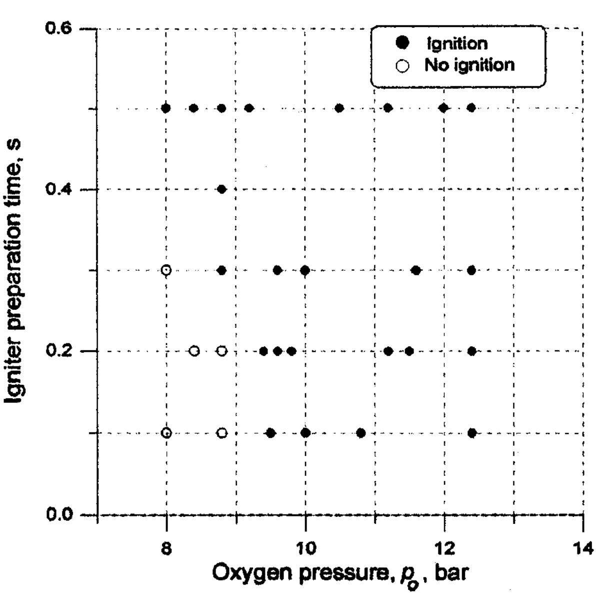

Fig. 3 Effect of pressure p_o and igniter preparation time on ignition.

about 7 kg, and the 2.4 L oxygen tank was the heaviest component: 1.66 kg designed for nominal pressure of 200 bar. Hence, the ignition system took no account of a compromise between mass and number of ignitions, and, therefore, it can be lighter for flight applications.

Conclusions

An ignition system based on resonance igniter was designed and tested, which 1) can operate independently of engine propellant lines only at the cost of the energy of stored compressed oxygen; 2) contains reduced number of components and can be designed as a modular unit, for a wide range of mass flow rate and mixture ratio; and 3) allows up to eight ignitions with an oxygen tank of 2.4 L under 170 bar, for 2 s of torch duration and $33 \cdot 10^{-3}$ kg/s of torch flow rate.

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Experimental Investigation of Pulsatile Flow in Circular Tubes

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Nomenclature

d = tube diameter
Q = volume flow rate
Re = Reynolds number
r = distance from tube axis
T = period
v = velocity
α = frequency parameter
λ = flow ratio
ν = kinematic viscosity
ρ = fluid density
σ = Reynolds normal stress
ω = angular frequency

Introduction

THE investigation of pulsatile Newtonian fluid flow in circular rigid pipes was performed by the authors. The aim of the research was to deepen the knowledge of impact of model geometry and flow characteristics on origination and development of Reynolds stress and on the value of energy loss during pulsatile flow. Interesting results that were obtained will be used in practice. Velocity profiles were measured with a laser-Doppler anemometer. The assemble-average velocity profiles and the Reynolds normal stress have been experimentally evaluated. Knowledge of origination and development of turbulent disturbances helps us to create an image of transformation of flow into turbulence. The evaluation of the Reynolds normal turbulent stress helps us to determine the values of Reynolds tangential stress, which causes hydraulic loss in the tubes. In hemodynamics the Reynolds tangential stress has a great importance for possible damage of blood elements and inner surface of blood vessels.

At the same time the pressure loss in circular tubes of a constant cross section was measured, and it was evaluated in dependence on parameters of pulsatile flow. The result of this measurement was the determination of dependence of loss coefficient on flow characteristics. Knowledge of these relationships can result in the minimization of the energy loss in pulsatile flow.

We have also evaluated velocity profiles, Reynolds stress, and the pressure loss in singularities formed by sudden expansion and consequential sudden contraction of the tube. The result is dependence of loss coefficients on the pulsatile flow parameters. Knowledge of these relationships provides for better understanding of the pulsatile flow mechanisms exploitable in industrial applications as well as in hemodynamics, and it can result in remarkable energy savings.

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The laminar-turbulent transition process in oscillatory pipe flow has been investigated by Hino et al.,[1] Ramparian and Tu,[2] and Eckmann and Grotberg.[3] Although there have been some attempts to analyze the problem of stability in periodic flows, much remains to be studied in pulsatile flow.

Experimental Apparatus

The experimental investigation of pulsatile flow of a Newtonian fluid was performed. A description of the experimental apparatus has been provided by authors in their paper.[4]

The measured flow is a result of superposition of stationary flow and periodic oscillations. A small water station supplies steady flow. The source of periodic oscillations is a piston with sinusoidal mechanism.

The flow is characterised by a flow ratio λ and a frequency parameter α. $\lambda = Q_{\mathrm{pm}}/Q_s$ is a ratio between the maximum amplitude of the oscillatory component of the volume flow rate Q_{pm} and the corresponding stationary component Q_s. Frequency parameter is $\alpha = d/2\sqrt{(\omega/\nu)}$. The measurement was performed for two parameters λ (0, 45 and 0, 9) for a number of values α (8–30) and for five stationary components of the flow Q_s (1–5 l min^{-1}). The velocity was measured at 30 points along pipe diameter.

Amplitude and frequency of pulsation are set by the adjusting of a piston stroke and a number of asynchronous motor revolutions. The height of water level in the overflowing vessel and its temperature is kept constant during the measurement. Re_m is Reynolds number for stationary velocity $\bar{v} = 4Q_s/\pi d^2$.

Velocity Measurement

A single-channel laser-Doppler anemometer operating in a forward scattering mode was used to obtain the local value of fluid velocity. For these experiments the model is a circular tube with

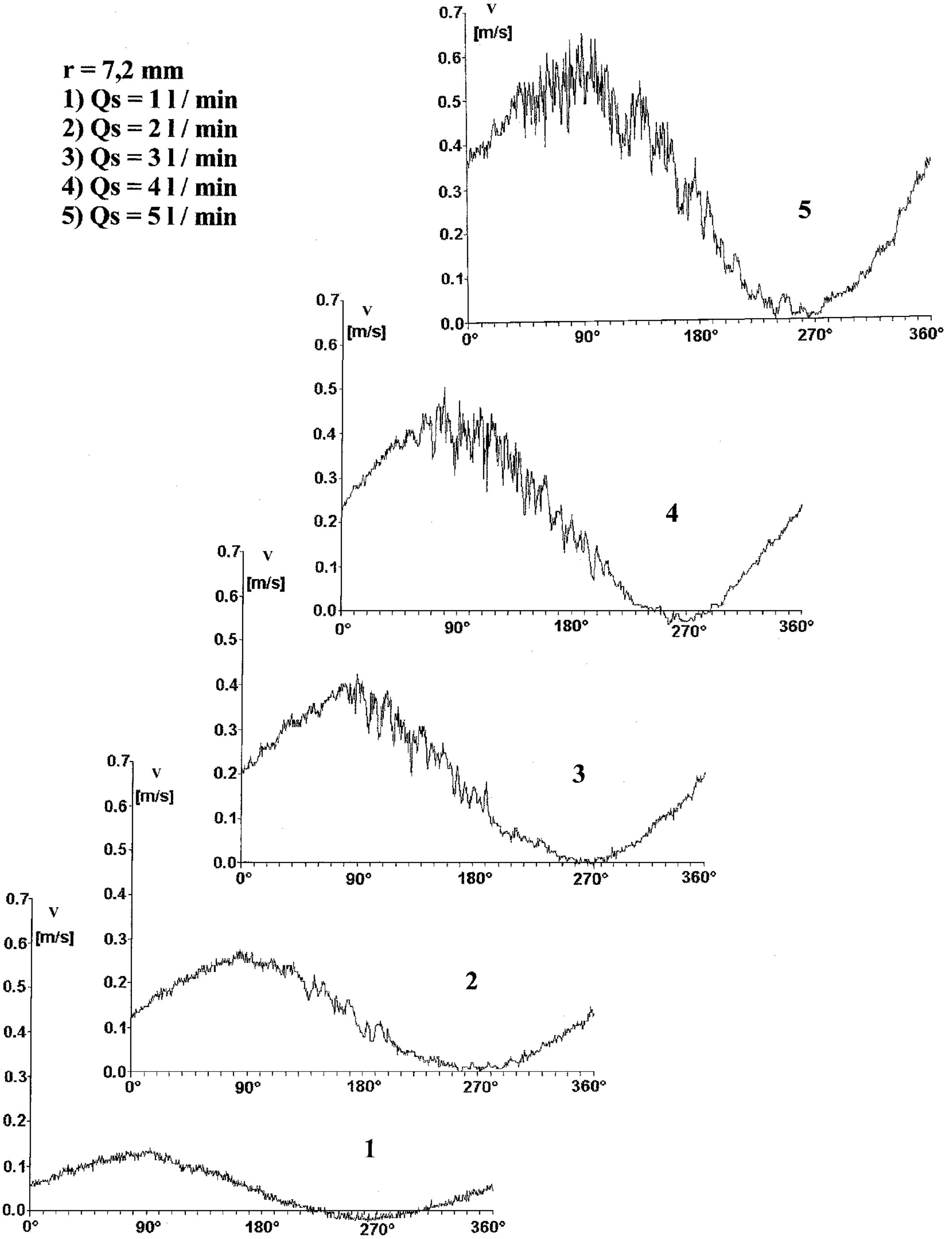

Fig. 1 Experimental instantaneous velocity for $\alpha = 11$, and $\lambda = 0, 9$.

rigid walls and a diameter of 20 mm. The system was used for velocity and Reynolds normal stress estimation.

The mean velocity is calculated from the formula

$$\bar{v} = \frac{1}{T}\int_0^T v\,\mathrm{d}t$$

where $v = v(t)$ means instantaneous velocity. The ensemble average of velocity is given by the formula

$$\langle v_k \rangle = \frac{1}{N_p}\sum_{j=1}^{N_p} v_{jk}$$

where index j counts periods and index k counts phases in period. N_p is a number of measured periods, and v_{jk} is velocity in the jth period and kth time of period. Number of periods is $N_p = 50$, and number of phases is $D_p = 720$ in each point (it represents 36,000 data). The fluctuating component of velocity $v'_{jk} = v_{jk} - \langle v_k \rangle$.

Experiments on transition to turbulence in a pulsatile pipe flow were performed for various values of parameters Q_s, λ, and α in several points along the diameter. Experimental instantaneous velocity records at point distant $r = 7, 2$ mm from tube axis for Q_s (1–5 l min^{-1}), $\alpha = 11$ and $\lambda = 0, 9$ are shown in Fig. 1. The turbulent plugs are clearly visible (especially during the deceleration part of the cycle) for $Q_s = 2$, 3, 4, and 5 l min^{-1}.

Values of instantaneous velocity depend on radial position of measured point. Turbulent plugs occur at different phases of the period, depending on Q_s, λ, α, and r, and are phase locked.

Dependence of Reynolds Normal Stress on Flow Characteristics

The Reynolds normal stress will be calculated from

$$\sigma = \rho\left\langle v_k'^2 \right\rangle = \frac{\rho}{N_p}\sum_{j=1}^{N_p} v_{jk}'^2$$

The traces of normal stress variation for $Q_s = 1$–5 l min^{-1}, $\alpha = 11$, $\lambda = 0, 9$ and point $r = 7, 2$ mm are shown in Fig. 2.

From the figure arises the fact that the flow at $Q_s = 1$ l min^{-1} can be considered as laminar. The values of mean Re_m, minimal and maximal Reynolds numbers for particular values of Q_s are as follows:

$$Q_s = 1\,\mathrm{l\,min^{-1}} - Re_m = 1050, \qquad (Re = 110\text{–}1990)$$

$$Q_s = 2\,\mathrm{l\,min^{-1}} - Re_m = 2090, \qquad (Re = 210\text{–}3970)$$

$$Q_s = 3\,\mathrm{l\,min^{-1}} - Re_m = 3130, \qquad (Re = 310\text{–}5950)$$

$$Q_s = 4\,\mathrm{l\,min^{-1}} - Re_m = 4180, \qquad (Re = 420\text{–}7940)$$

$$Q_s = 5\,\mathrm{l\,min^{-1}} - Re_m = 5220, \qquad (Re = 520\text{–}9920)$$

Figure 3 shows the dependence of the value of normal stress σ_m on Q_s and λ. It is time-mean value within the disturbance.

Increase of λ causes a rise in the maximal value but a decrease in the mean value of stress in the turbulent disturbance area and phase shift of the beginning of the disturbance toward higher values.

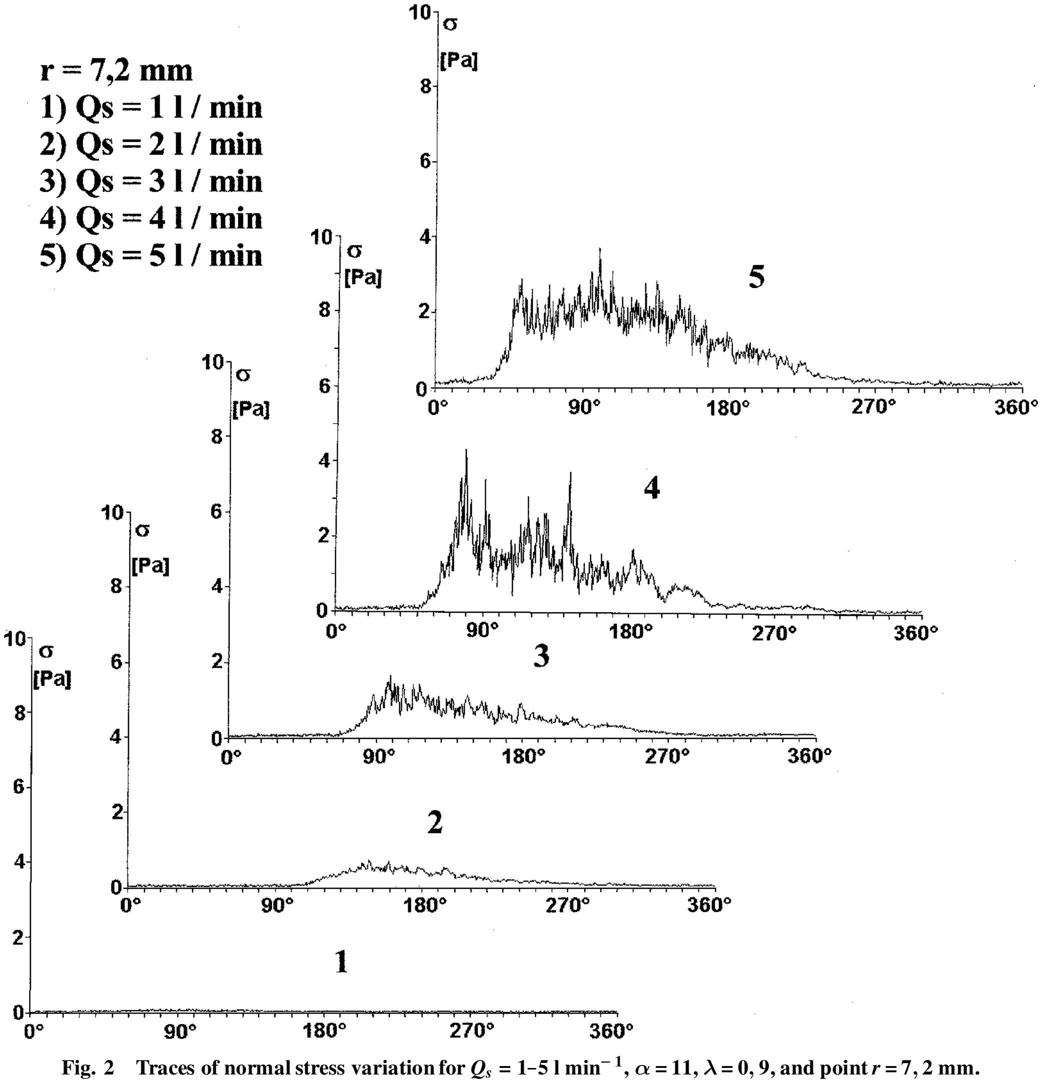

Fig. 2 Traces of normal stress variation for Q_s = 1–5 l min^{-1}, $\alpha = 11$, $\lambda = 0, 9$, and point $r = 7, 2$ mm.

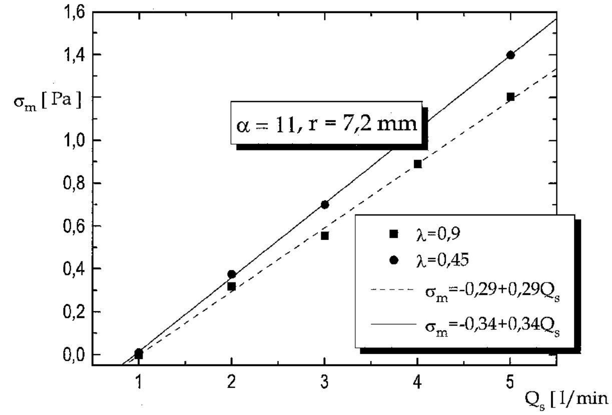

Fig. 3 Dependence of the mean value of normal stress σ_m on Q_s and λ.

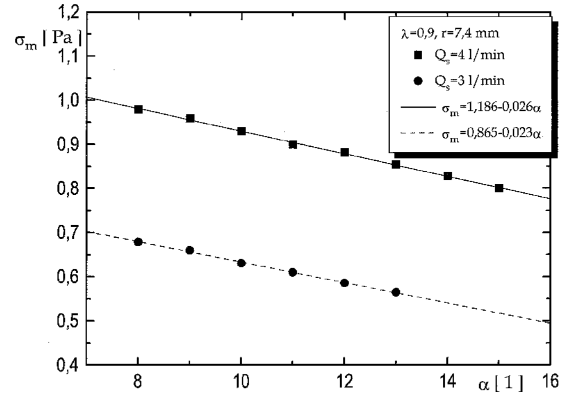

Fig. 4 Dependence of the mean value of stress σ_m on α for $Q_s = 3, 4$ l min^{-1}.

The dependence of the mean value of stress σ_m on α for $Q_s = 3, 4$ l min^{-1}, $\lambda = 0, 9$ and point $r = 7, 4$ mm can be read from Fig. 4.

Accuracy of Laser-Doppler Anemometer Techniques Used for Measurement of Velocity

Using the counting principle, the fundamental accuracy is set by setting of the laser-Doppler anemometer processor. The processor compares the outputs of two different counters; one of them utilizes the period length of five and the other of eight consecutive periods of the optic signals from a photomultiplier. The highest adjustable accuracy is 1, 5%.

Conclusions

From the results of the experiments carried out within the described range of Q_s, α, λ, and r, the following conclusions can be formulated:

1) At a certain measured point there is only one disturbance during a period.

2) For the first time the turbulent disturbances appear when $Q_s = 2$ 1 min^{-1}, $Re_m = 2090$, where Re_m is Reynolds number counted out from time-mean velocity.

3) The intensity of turbulent disturbance is growing in the direction of the tube wall.

4)The value of mean turbulent Reynolds stress of disturbance σ_m depends on Q_s, α, λ, and r. With the value of λ being constant, at certain measured point the value of σ_m increases simultaneously with the increasing value of Q_s (α being constant) and decreases simultaneously with the increasing value of α (Q_s being constant). When the value of λ increases (Q_s and α being constant), it causes an increase of the maximal value of stress in the area of turbulent disturbances but a decrease of the mean value of stress.

5) The beginning of turbulent disturbance depends on parameters Q_s, α, λ, and r. At a certain measured point the angle of the beginning of turbulent disturbance increases simultaneously with the increasing value of α (λ and Q_s being constant) and decreases with the increasing value of Q_s (λ and α being constant). When the value of λ increases (α and Q_s being constant), it results in a phase shift of the beginning of disturbance toward higher values.

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