Flow regimes in a multi-gap circular Couette-Taylor system with opposite rotating cylinders

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Abstract. This work investigates the flow structure in the gaps of a multi-cylinder circular Couette-Taylor system, which is a model of a two-rotor heat generator. The initial information for studying the flow structure was data on the magnitude of the resistance torque to rotors opposed rotation, as well as on the nature of the amplitude-frequency spectrum of pulsations of this torque, depending on the viscosity of the working fluid and the rotational speed of the heat generator rotors. The obtained data allow comparing the nature of hydrodynamic processes in the single and obtained multi-gap circular space of Couette-Taylor and calculating the parameters of structural formations in the multi-gap working space of the heat generator. At relative rotational speeds of rotors (3-50) rad/s, the main energy of flow pulsations (up to 90%) is found in the amplitude-frequency spectra in the frequency range (12-70) Hz. It is associated with vortices first described by Taylor, which are extended low-frequency regularly alternating spirals and vortex structures with right and left rotation in the region of higher frequencies (200–500) Hz; their frequency is determined by the width of the annular gaps of the multi-cylinder system.

1. Introduction

Exploratory studies of the most economical sources of heat for heating a liquid when utilizing mechanical energy have led to the idea of using the dissipative properties of a liquid to generate heat. In this case, due to the viscous properties of the liquid, when tangential stresses arise, both on the surface of solids and between the inner layers of the liquid, heat is released. In [1], a review of studies is given to highlight a wide range of problems of both the use of wind energy in electricity production and the direct conversion of this energy into thermal energy. Authors of [2] propose to consider a heat generator as a device for direct conversion of mechanical energy into heat, in which two coaxial counter-rotating multi-gap rotors form a circular Couette-Taylor system filled with a viscous working fluid. The proposed design is considered as a model of an efficient heat generator, which can be driven by two wind motors rotating towards each other. In such a system of annular channels, there is a circular flow, known as the Couette-Taylor flow. During the device operation, the working fluid, heated by high shear stresses, converts the supplied mechanical energy into thermal energy, which, through a special system, the main components of which are a circulation pump and a heat exchanger, can be transferred to a thermal energy accumulator for further use.

This work continues the authors’ research [1-6], presenting the results of experiments on the dependence of the power generated by such a heat generator on the relative angular velocity of rotation, the geometry of the proposed design and the viscosity of the working fluid. These experiments demonstrate that with a viscosity of the working fluid (6-25) · 10⁻⁶ m²/s and with a relative rotational
velocity of the rotors with a frequency of (4-5) Hz, the heat generator of the proposed design can reach a specific power that is significant for practical use (150-250) kW/m³.

The problem of the structure of viscous fluid flow and dissipation in the annular gap between rotating coaxial cylinders is classical and has a long history. The force of resistance to rotation depends on the nature of the flow and the viscosity of the working fluid in the gap between the rotating cylinders, the speed of rotation of the outer and inner cylinders, and the size of the gap between the cylinders and their height. The resistance torque to the rotation of the cylinders and the nature of pulsations of this torque depend on the Reynolds number, which is determined by the characteristic radius of the annular system, the relative angular velocity of cylinders rotation and the viscosity of the liquid in the annular gaps.

The multi-cylinder system investigated in this work has much in common with the single-cylinder circular Couette-Taylor system described in [7], but it is more complex in design and processes occurring in it. To study the structure of the flow of the working fluid in the annular gaps of such a design, it is necessary to create a multichannel telemetry system containing pressure and temperature sensors, combined by multichannel data collection and transmission equipment using radio channels and rotating rotors built into the structure.

In the proposed work, an attempt is made to experimentally study the flow structure in a multi-cylinder Couette-Taylor system, using a simpler method based on direct measurements of the resistance torque to rotation of the heat generator rotors, and the amplitude and frequency of pulsations of this moment, depending on the viscosity of the working fluid and the rotational speed of the rotors.

2. Experimental setup and technique

The basis of the experimental stand (see figure 1) is a two-rotor model of a heat generator (1) with two independent electric drives (2, 3), two rotor speed sensors (10) and a torque sensor of the resistance torque (7). The generator rotors structurally consist of two sets of the same type of metal cylinders of variable diameter (wall thickness 1.5 mm) nested in each other's annular gaps. Counter rotating rotors form a multi-cylinder circular Couette-Taylor system, consisting of 13 circular cylindrical channels (six 2 mm wide channels and seven 3.6 mm wide channels). The height of the cylinders is 50 mm, and the diameter of the cylinders is from 198 to 302 mm. A detailed description of the experimental setup and the design of the heat generator is given in [6].

Figure 1. Setup diagram: (1 - heat generator; 2 - upper electric drive; 3 - lower electric drive; 4 - control units for rotation speed of electric drives; 5 - thermal insulation; 6 - shut-off and control valves (manual balancing valves); 7 - dynamometer; 8 - temperature sensor; 9 - thermometer electronic unit; 10 - tachometer sensors; 11 - data processing unit; 12 - flow meter; 13 - circulation pump; 14 - thermostatic container with working fluid).

The rotors of the experimental setup could rotate at different relative velocities in opposite directions. The velocity was set by voltage regulators (4). The rotation frequency was controlled and measured with a two-channel frequency meter.

The system of annular channels of the heat generator was filled with a viscous working liquid with known properties. During the operation of the heat generator, the liquid was heated due to the dissipation of mechanical energy in the annular channels. In this case, the kinetic energy of the mechanical drive of the heat generator was completely converted into thermal energy. In the experiments, we used 3 types
of working fluid (table 1), being water-glycerin solutions of different concentrations. The viscosity and density of the solution were determined by its temperature and the concentration of water and glycerin.

Table 1. Working liquid properties.

| №  | Weight concentration, % | T, °C  | ν·10⁴, m²/s | ρ, kg/m³ |
|----|-------------------------|--------|-------------|---------|
| 1  | Water 30, glycerin 70   | 26-50  | 6-19        | 1180-1160 |
| 2  | Water 20, glycerin 80   | 28-56  | 15-32       | 1200-1180 |
| 3  | Water 12, glycerin 88   | 27-45  | 24-83       | 1220-1210 |

The dependence of the viscosity and density of working liquids on temperature was determined in a special series of experiments. The measurement results were tabulated and used in the processing of experimental data.

All experiments were carried out with opposite rotation of the heat generator rotors. The rotors rotated at the same fixed angular velocities so that their relative angular velocity of rotation was \( \Omega = 44 \) rad/s. During the experiments, the internal volume of the heat generator with the help of shut-off and control valves 6 (see figure 1) was disconnected from the thermostated container with the working fluid 14 (see figure 1).

To register the value of the resistance torque, the stator of the upper motor of the electric drive was fixed on a vertical freely rotating axis and connected to the strain gauge of the dynamometer through the shoulder \( h = 0.115 \) m. This system allowed registering the friction-induced resistance torque and the pulsations of this torque. Dynamometer 7 (see figure 1) was calibrated in a static mode using standard weights before the experiments. The calibration dependence of the measured resistance torque on the dynamometer output signal was linear, and the uncertainty in measuring the resistance torque was \( \sim 1\% \) of the upper limit of measurement of the dynamometer (20 N·m). Parasitic losses due to friction in bearings did not exceed 5% of the upper limit of the dynamometer measurement (20 N·m), their value was determined in special experiments in the absence of a working fluid, and they were considered when processing experimental data.

The experiment was carried out according to the same scheme with each working fluid. With the help of control units for revolutions of electric drives 4 (see figure 1), the counter rotation of the upper and lower rotors of the heat generator with a relative angular velocity of rotation of the rotors \( \Omega = 44 \) rad/s was established. Since the internal volume of the heat generator filled with the working fluid was disconnected from the thermostated container 14 (see figure 1), the temperature of the working fluid during the experiment increased continuously due to the release of heat in the heat generator. By continuously monitoring (measuring) the temperature of the working fluid, it was possible at any stage of the experiment to determine its viscosity using calibration curves. During the experiment, an automated system for recording experimental data every 3 minutes recorded the current time, the temperature of the working fluid, the magnitude of the resistance torque of the rotors, the graphs of the torque oscillograms and the amplitude-frequency spectra of pulsations of the rotors resistance torque.

3. Results and discussion

The main task of the work was to investigate the structure of the flow of a working viscous fluid in the gaps of a multi-cylinder Couette-Taylor system, based on the analysis of experimentally recorded oscillograms of the resistance torque of the heat generator and the pulsations of its instantaneous value and amplitude spectra of pulsations of this torque in the frequency range from 14 Hz to 600 Hz. The results obtained were compared with the known research results for a flow in a single gap, in particular, with the results of [7]. In [7], a system formed by two coaxial independently rotating cylinders was investigated. Based on the performed studies, the authors presented a detailed map of flow regimes in the annular gap of cylinders rotating relative to each other as a function of the Reynolds numbers of the inner and outer cylinders \( \text{Re}_i \) and \( \text{Re}_o \), respectively. Here \( \text{Re}_i = R_i \cdot \delta \cdot \Omega / \nu \), \( \text{Re}_o = R_o \cdot \delta \cdot \Omega / \nu \). Figure 2 shows a fragment of this map corresponding to the counter rotation of the outer and inner cylinders.
The oblique line in figure 2 corresponds to the operating modes of the multi-cylinder heat generator considered in the work, and the red and blue points on this line correspond to the Reynolds numbers calculated for the gaps of the heat generator with a width of 2 mm and 3.6 mm, respectively.

This line crosses regions with different flow regimes in annular gaps [7]: AZI (azimuthal laminar flow with weak Ekman vortices), IPS (interpenetrating spirals), SPI (spiral vortices), TVF (Taylor vortex flow), WIS (wave interpenetrating spirals), MWV (modulated wave vortices). Analysing the position of these points on the map (figure 2), it is possible to estimate with some degree of confidence, which flow modes are present in the annular gaps of a real heat generator under certain operating conditions.

For the convenience of comparing the experimental data obtained in the multi-cylinder Couette-Taylor system with the data of [7] for a system with one annular gap, the experimental design of a heat generator can be represented as an equivalent in power Couette-Taylor system with a single annular gap. This representation was successfully used in our work [1]. The following values were taken as the basis for such an equivalent channel:

- the radius of the inner cylinder is equal to the average value of the radius of the multi-cylinder system \( R_i = R_{av} = 0.124 \) m;
- the height of the equivalent channel is equal to the sum of the heights of all channels of the heat generator \( H = \sum H_i = 13 \cdot 0.05 = 0.65 \) m;
- the volume of the equivalent channel is equal to the sum of the volumes of the annular gaps of the heat generator \( V = \sum V_i = 1.4 \cdot 10^{-3} \) m³;
- the width of the equivalent channel (two cylinders gap) is equal to \( \delta = V/(2\pi R_{av} N) = 0.0027 \) m;
- radius of the outer cylinder of the equivalent channel \( R_o = R_i + \delta \).

This approach allows reducing the multi-cylinder system of an arbitrary heat generator to an equivalent classical single channel with the Couette-Taylor flow and transferring the obtained data to other sizes and geometry of heat generators.

Further, when analyzing the results obtained, the Reynolds number \( Re = R_0 \delta \Omega/\nu \) is used as an argument for the outer cylinder of the equivalent Couette-Taylor system with a single annular gap in the case when both cylinders rotate with the same angular velocity \( \Omega/2 \) in opposite directions.

For working fluids No. 1, No. 2 and No. 3 (see table 1) Figure 3 gives the dependence of the specific power of the heat generator on the Reynolds number for a constant relative angular velocity of rotation of the rotors (\( \Omega = 44 \) rad/s) with decreasing viscosity of the working fluid (with increasing temperature working fluid). The power released by the equivalent system is determined by the formula \( N = \Omega M \) [1,6]. Specific power is defined here as the power released by the heat generator, referred to the volume of the working fluid \( V \), located in the annular gaps of the heat generator: \( N_s = N/V \) [kW/m³].

**Figure 2.** Fragment of the flow regime map [7] and experimental data. Red marker - 2 mm gap, blue - 3.6 mm.

**Figure 3.** Dependence of the specific power of the heat generator on the Reynolds number at a constant relative angular velocity of rotation and a decreasing viscosity of the working fluid.
In accordance with Figure 3, the power of the heat generator with an increase in the Reynolds number due to viscosity at a constant relative angular velocity of rotation of the rotors decreases according to the dependence close to hyperbola.

Figure 4 shows an example of time oscillograms, where the dynamometric system recorded the behavior of the instantaneous resistance torque to the heat generator rotors for two values of the working fluid viscosity: \( \nu = 18 \cdot 10^{-6} \text{ m}^2/\text{s} \) and \( \nu = 6.8 \cdot 10^{-6} \text{ m}^2/\text{s} \). Figure 4 implies that, in addition to pulsations of small amplitude, there are stochastic pulsations of the resistance torque with an amplitude of up to +/- 25% of the averaged value of this torque, and the probability of occurrence of such pulsations is of a random nature of damped low-frequency nonharmonic oscillations.

Analysis of oscillograms in figure 4 shows that the pulsations of the resistance torque of small amplitude and high frequency are superimposed on oscillations, the frequency of which is significantly lower. This behavior of the resistance torque may be associated with spiral vortex formations arising in the gap space of the annular Couette-Taylor flow and described in [7]. Such spiral formations can occupy the entire circumference of the annular gap of the heat generator or some part of it.

Figure 5 shows the amplitude-frequency spectra of pulsations of the integral resistance torque for four values of the working fluid viscosity, covering the entire investigated range of viscosity: \( (54 \cdot 10^{-6}, 27 \cdot 10^{-6}, 16.5 \cdot 10^{-6} \text{ and } 6 \cdot 10^{-6} ) \text{ m}^2/\text{s} \).

![Figure 4](image1.png)

**Figure 4.** Oscillograms of pulsations of the resistance torque to the rotors for two values of viscosity:
(a) \( \nu = 18 \cdot 10^{-6} \text{ m}^2/\text{s}, \Omega = 3 \text{ Hz} \); (b) \( \nu = 6.8 \cdot 10^{-6} \text{ m}^2/\text{s}, \Omega = 3 \text{ Hz} \).

![Figure 5](image2.png)

**Figure 5.** The pulsations spectra of the resistance torque at a constant relative velocity \( \Omega = 44 \text{ rad/s} \) for four values of viscosity.
Figure 5 shows that in the entire considered range of viscosities of the working fluid, the spectra of the energy distribution over frequencies are practically similar. In these spectra, reflecting the distribution of pulsation energy by frequency, three frequency sub-ranges can be distinguished: low-frequency (0.2 - 60) Hz and two high-frequency (230 - 300) Hz and (460 - 540) Hz. According to the above analysis of the oscillograms, it may be assumed that the low-frequency part of these spectra reflects spiral structures of the flow, while the high-frequency part corresponds to vortex structures.

Figure 6 shows the amplitude-frequency spectrum of the low-frequency sub-band in more detail. It may be noted that in the low-frequency region (14-60) Hz, there are groups of pulsations with a constant frequency and with the dependence of the amplitude of pulsations on viscosity. The spectra for all values of viscosity exhibit characteristic resonance processes with frequencies \( f = (19, 27, 35, 41, 48, 51) \) Hz. The analysis shows that the pulsations of these frequencies are determined by the radius of the cylinders and the gap of the slots in which the pulsation data exist at a certain combination of viscosity and rotational speed of the rotors (i.e., the Re number).

Analysis of the data on the amplitude and frequency of pulsations allows distinguishing six subregions \( (F_1-F_6) \) in the low-frequency region, where the relationship between the effective value of the amplitude of pulsations and the viscosity of the working mixture is observed \((\nu = 54, 27, 16.5, 6) \times 10^4 \text{ m}^2/\text{s} \text{ from})\). The main part of the thermal energy of pulsating structures (up to 90%) is released in the regions \( F_2, F_3, F_4 \) of the frequency range (14 - 40) Hz (see table 2).

![Figure 6. Amplitude-frequency characteristics of the region of spiral flow structures.](image)

Table 2 shows the wavenumbers of these frequencies and the corresponding maximum values of the pulsation amplitudes.

| Pulsations region | \( F_1 \) | \( F_2 \) | \( F_3 \) | \( F_4 \) | \( F_5 \) | \( F_6 \) |
|-------------------|-----------|-----------|-----------|-----------|-----------|-----------|
| Average pulsations frequency, Hz | 14.8 | 19.7 | 27.1 | 35.5 | 47.5 | 56.3 |
| Maximum pulsations amplitude, N·m | 0.072 | 0.082 | 0.125 | 0.11 | 0.04 | 0.01 |
| Wave number, W | 0.41 | 0.32 | 0.24 | 0.19 | 0.13 | 0.12 |

Figure 7 shows the high-frequency region of the spectra (200–600) Hz, where two groups of pulsations with a small amplitude of harmonics arising under the influence of vortex structures are observed.
Figure 7. High-frequency region of spectra corresponding to vortex flow structures.

From the comparison of data on the amplitude of pulsations in high-frequency regions (№2, 3) with data for region No.1 (see figure 5 and table 2), the corresponding vortex structures of the flow make an insignificant contribution to the heat production in the circular system of the Couette-Taylor circular flow.

4. Conclusions
A method has been proposed for studying dissipative processes in a multi-cylinder system by analysing the average value of the resistance torque to the heat generator rotors and the amplitude-frequency spectra of pulsations of the instantaneous value of this torque.

The signal from the original digital tensometric dynamometer has been analysed directly to measure the resistance torque and its pulsations in the circular Couette-Taylor system.

In the entire considered range of viscosities of the working fluid, the amplitude-frequency spectra of the energy distribution over frequencies are practically similar, but the dependence of the amplitude of the harmonics on the viscosity is observed: with increasing viscosity, the amplitudes increase.

It is shown that the deviation of the instantaneous value of the resistance torque from the average value mainly depends on the low-frequency energy-containing formations (spirals). The parameters of these formations are determined by the design features of the annular clearances of the multi-cylinder Couette-Taylor system and the viscosity of the working liquid of the heat generator.

The high-frequency region (from 220 to 600 Hz) is associated with vortex structures, the frequency of which is determined by the width of the annular gaps δ. Since in the tested design of the heat generator there were two groups of annular gaps (3.6 mm and 2.0 mm wide), two subregions corresponding to these values of the width of the annular gaps: (230-280) Hz and (470 - 520) Hz were observed in the high-frequency region of the spectra of pulsations.

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