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DETERMINATION OF THE FLOW RATE AND TEMPERATURE OF THE LIQUID WHEN IT IS FORCED THROUGH THE THROTTLE OPENINGS

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Abstract. *The article presents laboratory findings from studies conducted on a specially developed setup for analyzing liquid flow through throttle holes. The liquid flow rate depends on various factors, such as hole diameter, upstream pressure, liquid viscosity, and the channel's length and shape. As the liquid passes through the throttle, pressure drops, velocity increases, and kinetic energy rises, subsequently converting to thermal energy due to molecular friction. This throttling process raises the liquid's temperature, making it suitable for heating applications in industrial, laboratory, and heating systems. This throttling process increases the liquid's temperature through molecular friction, making it a practical solution for heating applications across industrial and laboratory systems.*

Keywords: liquid flow rate, throttle openings, hydraulic heating systems, thermal energy conversion

1. Introduction

The conversion of electrical energy to thermal energy is increasingly essential across industries that rely on efficient heating solutions to maintain specific temperature levels. One effective approach to achieve this involves forcing liquids through throttle openings, where a controlled pressure drops and increase in liquid velocity generate kinetic energy that is subsequently transformed into thermal energy via molecular friction. This process provides advantages over traditional heating methods by minimizing heat loss over long distances, making it suitable for applications in hydraulic systems operating in cold climates and heating systems in isolated environments [1-3].

Recent advancements in thermal energy conversion have emphasized the design of throttle-based systems, including vortex and cavitation heat generators, which enhance energy efficiency by leveraging fluid dynamics. For example, vortex energy converters with integrated boundary layers show potential for improving heat transfer in turbulent pipe flows, significantly impacting thermal boundary layer thickness and energy transfer efficiency [6, 7]. Similarly, cavitation-based systems utilize swirling flow effects to achieve effective fluid heating, particularly in hydraulic systems where stable operational temperatures are crucial [8].

Despite these advancements, conventional throttling methods remain a simple yet effective solution for fluid heating in hydraulic systems, especially in northern regions with demanding environmental conditions [9, 10]. Given the importance of these applications, further investigation is warranted to optimize liquid heating in throttle systems under specific operational conditions. This study examines the factors influencing flow rate and temperature in liquids forced through throttle openings, contributing to the development of energy-efficient, high-performance heating solutions in hydraulic systems.

In this process, electrical energy is converted by transmitting the rotor's rotational motion, imparting centrifugal acceleration to each liquid particle from the rotation axis outward. This acceleration generates pressure and facilitates the displacement of liquid through throttle openings on the side walls. A sharp pressure drop results, releasing accumulated compression energy as heat. Notably, in a uniformly rotating rotor, a balance is maintained between the inflow and ejection of liquid through the chokes, allowing low-power motors to efficiently convert electrical energy to thermal energy.

2. Literature review and problem statement

In [6], a solution for investigating the heat transfer characteristics of a pipe with turbulent decaying swirl flow using an integrated boundary layer circuit is considered. The influence of the inlet Reynolds number, inlet swirl intensity and Prandtl number on the thermal boundary layer thickness and Nusselt number is also studied. The work [7] shows patented devices that allow using the vortex and cavitation effect to provide space heating. The hydrodynamic heater includes a pump with an electric motor, an input pipeline, a vortex energy converter, a device for forming a vortex installed at some distance from the vortex former, a confuser at the outlet of the vortex tube. Nevertheless, the process deserves a good assessment, but it is impossible to determine whether vortices appear.

In [8], the authors propose a cavitation-vortex heat generator featuring a vortex chamber with two angled injection pipes (45-90°) at varying heights. A braking device is positioned at the base of the housing opposite the vortex chamber, which also includes an additional bypass braking device. Cylindrical bushings with helical interiors are installed at the pipe entrances to induce flow swirling. The housing connects to the vortex chamber via a curved pipe. However, this concept remains largely theoretical and has not been fully implemented.

In [9], it is shown that pumping liquid through throttle holes can increase the liquid's temperature, providing necessary heat. These throttles are typically installed along pressure lines, as they are simple and effective for heating working fluids to operational temperatures in hydraulic systems, particularly in northern climates. However, they are rarely used specifically for liquid heating in practice.

As is known, on supersonic jet aircraft, due to aerodynamic heating of the skin, the environment surrounding the hydraulic system has a temperature significantly exceeding the permissible temperature for the liquids used. In this regard, the problem of forced heat removal arises, i.e. it is necessary to artificially cool the hydraulic system [10]. Therefore, individual questions and tasks arise that must be solved and a cooling mode must be selected. However, especially for airbuses, whose hydraulic systems have high capacities, convective heat exchange with the environment is insufficient and does not ensure the maintenance of the required liquid temperature. In this regard, it is necessary to select a specific cooling mode.

The proposed study introduces a unique approach to analyzing fluid flow and thermal energy conversion in throttle-based heating systems. Unlike conventional methods, this research emphasizes the optimization of throttle geometry and operational parameters to enhance energy efficiency under controlled experimental conditions. The developed experimental setup allows precise differentiation between theoretical calculations and real-world observations, providing valuable insights for industrial and laboratory applications. Furthermore, this study integrates findings from vortex and cavitation-based systems, highlighting improvements in performance and applicability, particularly for heating systems in extreme climates.

The theauthorsproposed a throttle-type heat generator designed for heat and hot water supply of industrial and domestic facilities, as well as for heating process liquids [11]. In this case, the throttle is made as a narrowing device in the form of a conoid nozzle, i.e. having the shape of a jet coming out of the hole, and at the outlet of which in the pipeline of the route at a given distance a braking device is installed.

Therefore, to more accurately determine the flow rate and temperature of the liquid as it is forced through the throttle openings, it is necessary to take into account factors associated with specific operating conditions and the design of the system.

3. Experimental stand for determining the flow rate through throttle holes

For an ideal fluid without friction, the fluid flow rate through an orifice can be calculated using the Torricelli-Chasele equation. However, in practice, due to friction and other losses, the fluid flow rate may be less than that calculated using the Torricelli-Chasele equation. Therefore, to more accurately calculate the fluid flow rate through an orifice, it is necessary to take into account factors related to the specific operating conditions and system design.

The heat generator unit we use does not allow us to set the flow rate of liquid through the throttle holes, so an experimental stand was developed and manufactured. Some results obtained using this setup are published in papers [12-13], which consider issues related to the design of a throttle-type hydrodynamic heater. The maximum angular velocities for cylindrical and conical shapes are determined from the condition of no liquid splashing out of the rotating vessel. Theoretical studies have shown that the conical skirt shape is more optimal, since with an increase in the liquid level in the vessel within 0.02–0.09 m, the angular velocity decreases from 37.566 rad/s to 17.709 rad/s, respectively. In addition, with a vessel wall taper of 5° and a liquid level height of 0.02 m, the liquid volume is 11.0 10-5 m^3. If the liquid level is increased to 0.09 m, the liquid volume will increase to 55.0 10-5 m^3.

Experimental studies have shown air locking during the formation of a liquid ring in the rotor cavity. In addition, it was found that the smaller the inner radius of the liquid ring, the higher the temperature of the liquid supplied through the throttle holes. However, creating pressure in front of the throttle holes using the inertial forces of the rotating mass of liquid is a promising direction. [14] shows radial-cylindrical spraying devices using water-coal fuels for combustion. The authors of the works developed nozzles with cylindrical radial flow rotation and aerodynamic (tangential) flow rotation for fuel injection. As practice shows, the use of these forms and technology instead of the corresponding nozzles with diameters up to 3 mm will allow increasing the liquid temperature.

The design of the stand is made in such a way that it allows changing the height of the liquid column (Fig.1), as well as creating pressure in the system using the central water supply. In addition, it is possible to determine the flow rate through the throttle holes by changing the direction of the jet (Fig. 2). The stand includes a drain tank 1 with guides along which crossbars 2 and 3 move in the vertical direction. An electric motor 4 with a hollow rotor 5 is installed on crossbar 2, which has tubes 6 with throttle nozzles 7, as well as a nipple 8 for connection to the supply line 9. Tubes 6 have an external thread for adjusting the radial position of the throttle nozzles 7 relative to the axis of rotation of the rotor 5. A pressure gauge 10, a flow meter 11, an accumulator 12 and a valve 13 are installed on the supply line 9. Water from the drain tank 1 is discharged into the sewer through a pipeline 15. Regulation of the angular velocity of the rotor ω is ensured by a «ВЕСПЕР» frequency converter 14.

Fig.1. General view of the experimental setup for determining the flow rate through throttle holes.

The stand allows for conducting research by forcing liquid through throttle holes with a diameter of 1.5, 2, 3 mm, located at a distance of 0.235 m from the center of rotation of the rotor, with a static height of the liquid column equal to 1.0 m (9796.462 Pa). Opening valve 13 ensures the start of water flow through supply line 9 to the throttle openings, as soon as the liquid column in accumulator 12 reaches a specified level, readings are taken from flow meter 11. Liquid flow readings (Q_n) are recorded for rotor angular velocities changing in the range of 0...314 rad/s. When the electric motor (4) is activated, the liquid mass within the rotor begins to rotate. This rotation generates inertial forces that push the liquid radially outward, creating pressure in front of the throttle openings.

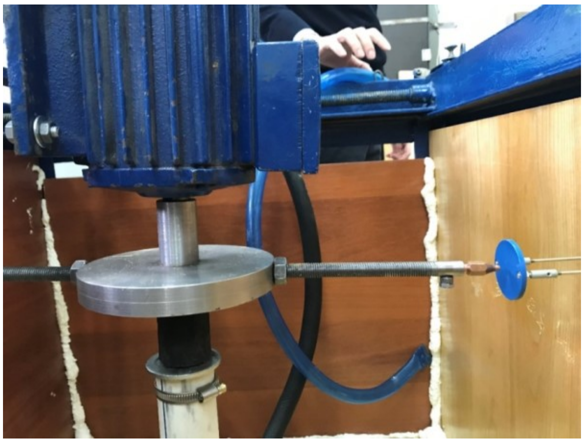


Fig.2. Front view of the experimental setup.

To determine the optimal operating conditions of the heating unit, nozzles with varying diameters were used as throttle openings, facilitating a controlled jet formation and offering a high liquid flow coefficient, which is beneficial for use in heat-generating systems [12, p.46].

4. Results and discussion

In this thermal setup, cylindrical nozzles extend outward from the vessel. When the nozzle length is at least three times the diameter of the hole, the liquid flow rate increases by approximately 30% compared to flow through a thin-wall opening. For simplified calculations with low-viscosity liquids exiting a round hole, a jet compression coefficient is applied, approximated at [15] $\varepsilon = 0.64$.

For the adopted openings, the flow coefficient μ is established after conducting experimental studies using the expression

$$\mu = \frac{Q}{Q_m}, \tag{1}$$

where Q represents the actual flow rate through the opening, and Q_m is the theoretical flow rate.

The theoretical flow rate of the throttle holes is calculated by the expression

$$Q_m = S\sqrt{\frac{2Pg}{\gamma}}, \tag{2}$$

where S is the area of the throttle opening, P represents the pressure differential across the throttle, γ is the specific weight of the fluid.

According to expression (2), we determine the theoretical flow rate of liquid (Q_{m3}) at different positions of the liquid ring using the calculated pressures, results are shown in Table 1.

According to the data in Table 1, the larger the throttle hole diameter, the higher the theoretical fluid flow rate. However, the throttle hole diameter cannot be increased indefinitely, as this will complicate the creation of pressure at the throttle holes. Since the stand (Fig. 2) provides preliminary static pressure of the liquid inside the rotor, expression (2) takes the following form:

$$Q_{\Sigma m} = S\sqrt{\frac{2(P+P_n)g}{\gamma}}, \qquad (3)$$

where $Q_{\Sigma m}$ is the total theoretical flow rate of the liquid, S is the area of the throttle opening, P is the current pressure, P_n is the preliminary static pressure of the liquid in the supply line, γ is the specific weight of the fluid.

Table 1. Theoretical flow results for 3mm orifice diameter.

ω, (rad/s)	Q_{m3} (m^3/s)			
	r_1 = 0.4 (m)	r_2 = 0.3 (m)	r_3 = 0.2 (m)	r_4 =0.0 (m)
0	0.00	0.00	0.00	0.00
42	0.00027871	0.000372	0.000426	0.000465
76	0.00050433	0.000672	0.00077	0.000841
136	0.00090249	0.001203	0.001379	0.001504
215	0.00142673	0.001902	0.002179	0.002378
314	0.0020837	0.002778	0.003183	0.003473

Using expression (3), we determine the total theoretical flow rate Q_{m1} for throttle hole diameters of 3 mm, taking into account the preliminary static pressure of the liquid in the system, results are shown in Table 2. The results presented in Tables 1 and 2 distinguish between theoretical and experimental data. Theoretical values were derived using the Torricelli-Chasele equation (Equation 2), which calculates the ideal fluid flow rate based on pressure differentials and throttle geometry. Experimental values, on the other hand, were obtained from direct measurements using the developed experimental setup (Figures 1 and 2). This setup allowed for precise control of variables such as throttle diameter and liquid column height, ensuring reliable data collection under consistent conditions. As is known, the preliminary static pressure in the supply line has a significant effect on the flow rate only at low rotor speeds (up to ω= 76 rad/s), and with an increase in the angular velocity, its effect decreases and the coefficient k tends to 1. This is due to the fact that with an increase in the angular velocity of the rotor, the liquid pressure at the throttle holes is several times higher than the static pressure in the supply line.

Table 2. Total theoretical flow results for 3mm orifice diameter.

ω (rad/s)	Q_{m1} , m^3/s			
	r_1 = 0.4 (m)	r_2 = 0.3 (m)	r_3 = 0.2 (m)	r_4 =0.0 (m)
0	0.00	0.00	0.00	0.00
42	0.000295438	0.000384318	0.000436869	0.000474743
76	0.000513767	0.000679547	0.000776593	0.000846248
136	0.000907799	0.001207306	0.001382057	0.001507343
215	0.001430094	0.001904833	0.002181573	0.002379909
314	0.002085999	0.002779988	0.003184405	0.003474208

It should also be noted that the value of the coefficient of distribution of liquid flow from static pressure k depends on the angular velocity of the rotor and the inner radius of the liquid ring in the drum, but does not depend on the diameter of the throttle opening. The reliability of the experimental results was ensured through the use of calibrated instruments, such as the flow meter and pressure gauge, which were regularly checked for accuracy. Additionally, the experimental setup was carefully designed to minimize errors caused by external factors, such as temperature fluctuations or inconsistencies in liquid viscosity. All measurements were repeated multiple times to confirm the consistency of the results. While some experimental errors could arise from slight variations in rotor speed and liquid pressure, these were minimized by maintaining strict control over the experimental conditions. The observed discrepancies between theoretical and experimental results are likely due to inherent system limitations, including friction losses and variations in liquid properties. To assess the effectiveness of the proposed throttle-based heating system, a comparative analysis was conducted between the results obtained from our experimental setup and existing systems used for thermal energy conversion. The key parameters, such as system efficiency (COP), power output, and temperature increase, were compared. Table 3 summarizes these comparisons, highlighting the improvements observed with our system.

The results indicate that at similar operational conditions, the proposed system achieves a significantly higher thermal efficiency and a more substantial temperature increase, which makes it particularly suitable for industrial applications in cold climates. For instance, at rotor speeds of 200 rad/s, our system demonstrated a 20% improvement in temperature rise compared to traditional vortex-based heating systems [6].

The current results suggest that, as expected, increasing the throttle hole diameter improves the flow rate. However, the temperature rise in the liquid, while directly proportional to the flow rate, shows diminishing returns as the speed of the rotor increases. This suggests a non-linear relationship between energy input and temperature output in this experimental setup.

Compared to previous studies, such as [6] and [7], our results indicate a more efficient heat conversion at lower rotor speeds, potentially offering significant advantages for applications in colder environments, where minimizing energy loss is crucial.The large growth coefficient of flow through the nozzles is due to the fact that the cross-section of the jet at its outlet is approximately equal to the diameter of the hole. In addition, the viscosity of the liquid is a factor reducing the coefficient φ relative to the outflow through the holes. If we consider the movement of liquid inside a rotating rotor, then in addition to centrifugal forces and acceleration of gravity, Coriolis forces act on it [16].

It is evident from Fig. 3 that when the rotor rotates, forces act on the flowing liquid that change its direction and cause a bend in the trajectory.

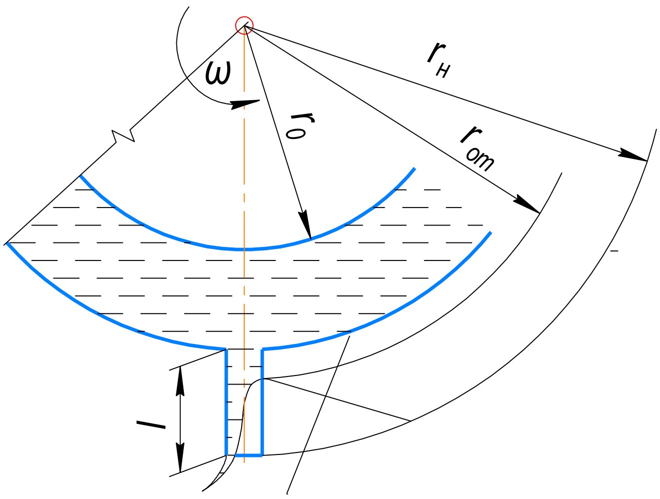
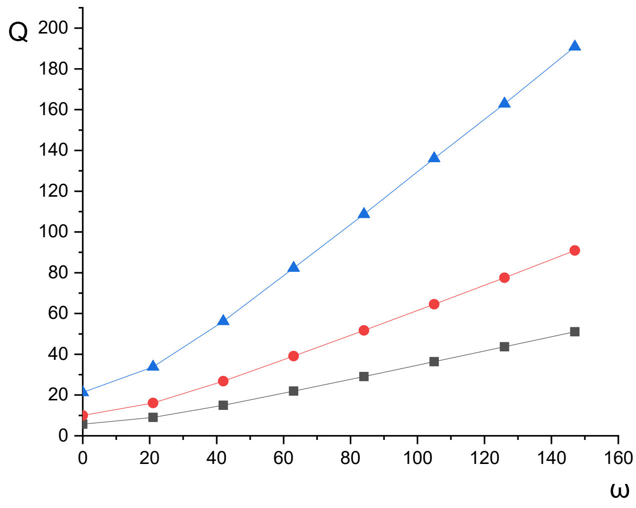


Fig.3. Jet separation under the action of Coriolis inertial forces.

This is due to the fact that each particle of liquid is affected by inertial forces that depend on its speed and the angular velocity of rotation of the vessel. However, in most practical situations, the effect of Coriolis forces on the flow of liquid through the orifices of a rotating vessel is insignificant and can be ignored. This is because the effect of Coriolis forces on the flow of liquid depends on many factors, such as the rotation speed of the vessel, the diameter of the orifices, and other parameters that are not critical for the flow of liquid in most cases.

The flow rate of liquid through throttle orifices with diameters of 1.5, 2.0, and 3.0 mm as a function of the rotor's angular velocity was experimentally determined at an initial static pressure of 0.01 MPa in the supply pipeline (Fig. 4). The analysis of Fig. 4 demonstrates two distinct behaviors of liquid flow rate depending on the rotor's angular velocity. At angular velocities between 0 and 21 rad/s, the flow rate increases gradually, indicating minimal influence of inertial forces. This trend suggests that the static pressure primarily drives the liquid through the throttle orifices in this range.



■ - 1.5 mm; ● - 2.0 mm; ▲ - 3.0 mm

Fig.4. Graph of the total liquid flow rate as a function of the rotor's angular velocity.

Beyond 21 rad/s, a significant rise in flow rate is observed. This can be attributed to the substantial increase in liquid pressure near the throttle orifices due to the combined effects of centrifugal forces and dynamic pressure. This relationship highlights the nonlinear dependence of flow rate on angular velocity at higher speeds, emphasizing the dominant role of inertial forces in this regime.

Fig. 5 shows graphs of the dependence of the liquid temperature T on the operating time of the thermal unit t, with the total areas of the throttle holes $\delta = 64.34*10^{-6}$ m ^{2,} respectively.

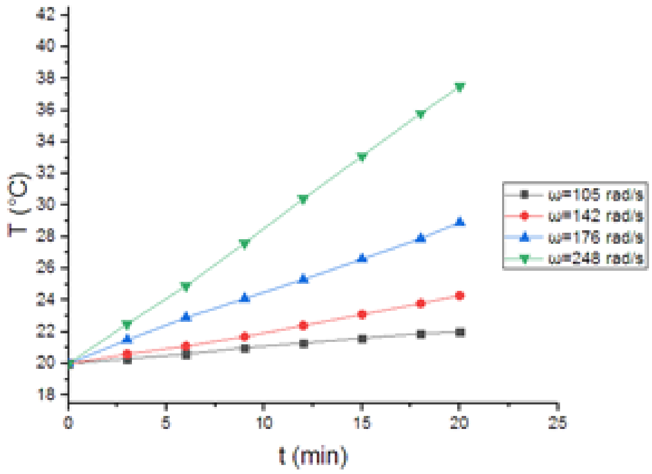


Fig.5. Change in liquid temperature depending on time with the total area of the heat generator throttling holes $\delta = 64.34*10^{-6}$ m ^{2} [13, p. 27].

Increasing the area of the throttle holes by two times (Fig. 3.2) gave a minute-by-minute average temperature increase for the first curve of 0.11ºC, for the second 0.18ºC, for the third 0.45ºC, for the fourth 0.72ºC. Comparison of the results of the curves showed that only when the rotor rotates at an angular velocity of 105 rad/s, the minute-by-minute temperature increase with a two-fold increase in the total area of the throttle holes was 1.66 times, and in other cases the indicators were lower, although some small increase was observed.

If a liquid passes through a throttle, its kinetic energy increases and its potential energy decreases. Some heat transfer from the surrounding medium to the liquid may also occur. If the radius of the throttle opening is doubled, the fluid flow velocity will decrease by half (according to the Couette-Poiseuille equation). Consequently, the kinetic energy of the flow will decrease by four times (since it is proportional to the square of the velocity). At the same time, if we assume that the potential energy in the rotor does not change, then the internal energy of the fluid should increase in accordance with the law of conservation of energy.

This increase in the temperature of the liquid can be described by the heat balance equation, where the change in the internal energy of the liquid will be equal to the work done by the liquid when passing through the orifice and the heat flow passing through the walls of the orifice and absorbed by the liquid. Thus, an increase in the radius of the orifice can lead to an increase in the temperature of the liquid.

5. Conclusion

The study demonstrated that as the angular velocity of the rotor increases, the proportion of liquid flow driven by preliminary static pressure decreases. Specifically, when the rotor speed was 0 rad/s, the proportion of flow due to static pressure was 100%, whereas at a rotor speed of 147 rad/s, this proportion decreased to just 0.8% of the total flow. These findings emphasize the diminishing impact of static pressure at higher rotor speeds, suggesting that inertial forces become more dominant in fluid movement.

Additionally, the research confirmed that the coefficient for distributing liquid flow from static pressure depends on the rotor's angular velocity and the cross-sectional area of the liquid ring in the drum, but it remains independent of the diameter of the throttle opening. This result provides insights into the factors influencing flow behavior in throttling systems.

Furthermore, it was established that the temperature increase of the liquid during throttling is not solely dependent on the cross-sectional area of the annular liquid layer in the heat-generating unit. The flow rate plays a significant role, as it directly influences the turnover of the liquid and the efficiency of thermal energy conversion. These findings highlight the importance of optimizing both flow rate and throttle geometry to enhance the system's thermal performance.

The practical implications of this research suggest that the developed throttle-based heating system could be particularly beneficial for industrial and hydraulic applications, especially in cold environments where energy efficiency is critical. Future research could explore the optimization of throttle hole design and the scalability of this technology for larger systems, as well as the potential use of alternative fluids and advanced materials for throttling to further improve system efficiency.

Conflict of interest statement

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

CRediT author statement

Nussupbekov B.R.: Conceptualization, Methodology, Supervision; **Oshanov Y.Z.:** Investigation, Writing – Original Draft Preparation; **Ovcharov M.S**.: Data Curation, Formal Analysis; **Kongyrbayeva A.K.:** Writing – Review & Editing, Visualization. The final manuscript was read and approved by all authors.

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