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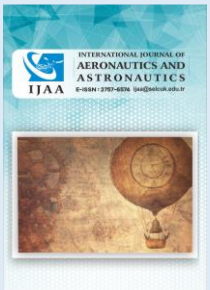

Research Article

Investigation of thermal behavior and orifice flow characteristics of aeronautic hydraulic servo-proportional valve spool-sleeve structure with numerical simulations

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ABSTRACT

In this study, the mechanical behavior under highest thermal conditions and flow characteristics of the hydraulic fluid of the servo-characterized proportional valve, which is one of the indispensable components of the aviation industry and used for hydraulic flow control, were investigated numerically. In the simulations, 50, 75 and 100 °C were selected as temperatures, and 0.2 mm, 0.6 mm and 1.2 mm spool stroke openings were used for hydrodynamic flow. Simulations were carried out for a pressure difference of 35 bar. As a result of the analysis, it was observed that there was no restriction in the movement of the spool-sleeve structure for a temperature of 75°C, excessive friction occurred in the spool-sleeve structure at 100°C and the movement was restricted. In addition, it can be said that hydraulic turbulences are effective in dispersing polluting particulate matter for all three spool strokes at a pressure difference of 35 bar.

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1. Introduction

It is seen that hydraulic fluid power is used effectively in the aviation sector with the developing industry. Valve structures are the most important system parts in order to benefit from the fluid power. In today's conditions, faster, more efficient and more precise aircraft aerodynamic structures and hydraulic systems suitable for them are preferred. Speed, pressure and position control are now the basic needs of hydraulic systems. Valves that perform these controls in servo feature have widespread use, especially in critical sectors such as aviation. In order for the spool-sleeve valve structures to show servo characteristics, a sleeve structure is designed for the movement of the spool in the valve body. Thus, the valve spool moves on the sleeve instead of the body directly. This allows a more precise control efficiency for the servo systems.

The spool-sleeve structure with high machining tolerance should be able to continue its movement uninterruptedly under all working conditions. Otherwise, the valve spool cannot perform its duty due to the spool-sleeve jamming and the valve cannot operate. If this tightness due to thermal effect exceeds the machining tolerance, the valve spool will either move by scratching the sleeve or it may get stuck completely under higher thermal stress and stop the movement. Considering that the control of the aerodynamic structures of the aircraft is provided by hydraulic systems, it is clear that the desired aircraft movement cannot be achieved due to this valve compression and the aircraft will face a possible accident.

The fact that the servo-proportional hydraulic valve structures are very sensitive causes the hydraulic fluid to be affected too much by the polluting effect. The pollutant particles in the hydraulic oil disrupt the structural geometry of the valve orifice and cause the fluid movement to occur in undesirable ways. This situation disrupts the precise movement control of the hydraulic oil flow and causes unwanted leaks. In addition, in some cases, these contaminant particles can prevent the valve's spool-sleeve movement and cause the valve to be locked. For this reason, it is necessary to obtain hydraulic oil vortex structures that will prevent particle accumulation at various points in valve designs. These vortex movements can disperse the pollutant particles and prevent the accumulation.

The thermal behavior and flow motion mentioned above can be simulated by various finite element calculation programs. Thus, thermal behavior and hydraulic flow motion can be investigated and transferred to designs without experimental work. Thus, both the difficulties of experimental work are eliminated and the costs can be minimized. Looking at the literature, various numerical studies have been carried out to investigate various problems on hydraulic valves [1-3]. Lisowski et al. [4] calculated the hydraulic fluid forces acting on the valve spool using a 3D computational fluid dynamics program and compared them with an experimental study. In their study, they developed different flow structures and achieved a 45% reducing effect on the force on the spool. Macor [5] experimentally investigated the effects of different spool angles on the spool force, and Baudry and Mare [6] conducted a correlation study on experimental results and CFD results in their study. Krishnaswamy and Li [7] carried out a study to increase the spool response using transient current forces. Yuan and Li [8] emphasized the effect of fluid viscosity and momentum flux, which were neglected in the spool design to increase the spool dynamics. Amirante et al. [9] examined the fluid dynamics behavior of a commercial hydraulic proportional valve in their study and showed the effects of reducing the spool force of some additional designs in order to reveal the valve performance. Amirante et al. [10] were evaluation of the driving forces acting on a 4/3 hydraulic open center directional control valve spool by means of a complete numerical analysis. A different approach is proposed for the axisymmetric analysis of a directional valve (4/3, closed center): whereas the RANS techniques are based on the time-averaged equations of the flow, in the present work the unsteady Navier–Stokes equations have been solved using the Direct Numerical Simulation (DNS), which provides important details on the instantaneous structures of the flow, affecting the valve performance by Antonio et al. [11]. According to Yaobao et al. [12] has been established a numerical model to predict the material removal rate and the worn profile evolution with erosion in hydraulic spool valves. In their study the particle trajectories are solved by a stochastic separated flow model based on eddy interaction, and the squeeze film is included as a part of a particle-wall interaction model. Yi et al. [13] are to make clarify the effects of the groove shape on the flow characteristics through computational fluid dynamics (CFD) and experimental investigations. The RNG k–e turbulence model is used to simulate the pressure

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distributions of the flow fields inside three notches with their corresponding typical structural grooves in order to analyze the changes of restricted locations along with the openings and, furthermore, to calculate the flow areas of the notes. In addition, many numerical and experimental studies have been carried out to examine fluid motion and fluid forces on the spool [14-17].

When the studies are examined, the main purpose of is insufficient literature in terms of the strain of thermal effects on the valve structure and the necessary structural changes to reduce the effects of pollutant particles on the spool-sleeve. In this study, the strain effects of high operating temperatures on the servo-proportional valve on the spool-sleeve and the turbulance structures were simulated and numerically investigated to prevent the accumulation of pollutant particles by using Solid-Works and ANSYS-19 academic software.

2. Model of the Servo-Proportional Valve System

A specially designed servo-controlled proportional valve structure was used in numerical analysis. The valve body, spool and sleeve of the valve are presented in Figure 1.

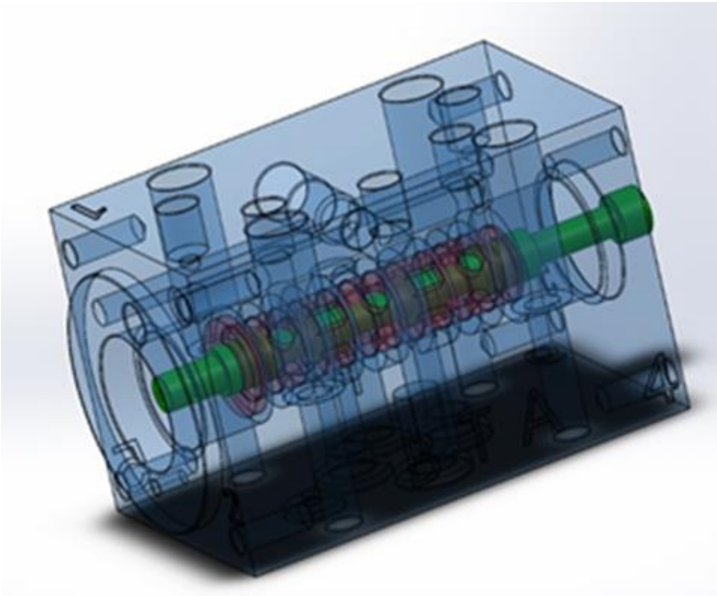

Fig. 1. 3-D view of the valve body, spool and sleeve.

When the valve body is examined under the transparent view, it is seen that the movement of the spool is on the specially lapped sleeve instead of the valve body. In order to provide servo characteristic control, it is imperative that the spool moves in the hive with a special surface quality. The disassembled body, sleeve and spool of the valve of the design are given in Figure 2. There are paths on which the hydraulic fluid moves on the valve body. Of these, P indicates the supply pressure line, A and B the directed oil lines, and T the return tank line. In normal operation, the hydraulic oil coming from P is directed to either the A or B line according to the desired direction with the help of a spool in the valve body.

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Fig. 2. Photograph of the disassembled valve.

When Figure 1 and Figure 2 are examined, symmetrical fluid paths are seen on the valve body and sleeve. 90º symmetrical hydraulic fluid paths have been designed for maximum 315 bar pressure and 32-40 lt/min flow range with the design and orifice calculation. It is calculated that the spool travel will have a full stroke of 2.4 mm (sum of both directions), and a stroke length of 1.2 mm is reserved for both line A and line B.

3. Numerical Analysis and Results

Proportional valves with servo characteristics cause serious malfunctions due to not being operated under appropriate conditions of use and cause malfunctions in the system in which they operate by not providing proper spool movement. The most important of these factors is mechanical frictions that caused by operating temperature. Due to its structure, the movable spool, which is produced very sensitively, and the sleeve-body structure suitable for it, cause frictions that caused by strains when the temperature range is exceeded. This is due to the fact that the hydraulic fluid is not well cooled and the valve is constantly in the loaded position and heats up, thus increasing its temperature. Considering that the valve will operate under thermal loads in a wide variety of applications, the need to perform strain simulations on the design has arisen. For this purpose, the spool-sleeve structure of the valve has been simulated for various operating conditions. The mesh structure of the spool-sleeve structure is shown in Figure 3.

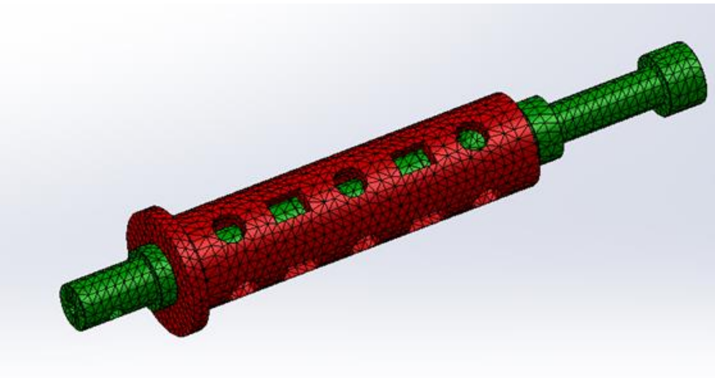

Fig. 3. Spool-sleeve mesh structure.

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Temperature values of 50 ºC, 75 ºC and 100 ºC were chosen in the analysis studies, and the simulation results are given in Figures 4a, 4b and 4c, respectively. It is known that under normal operating conditions, the hydraulic fluid and thus the valve structure heats up to 70 ºC. For this reason, the maximum temperature value of 100 ºC was chosen as a difficult operating condition.

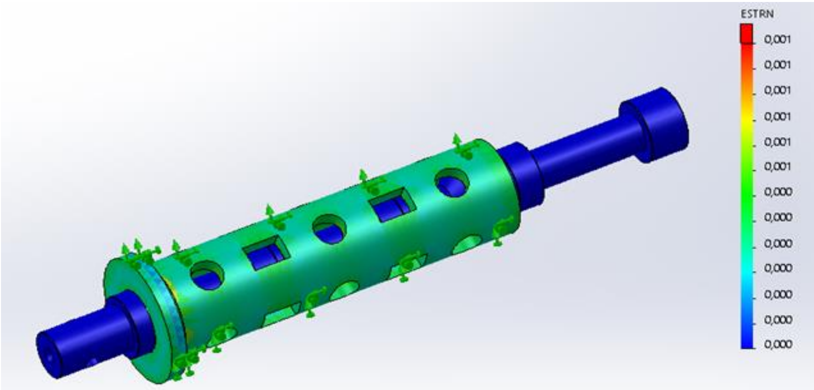

Fig. 4a. Spool-sleeve strain values (50 °C).

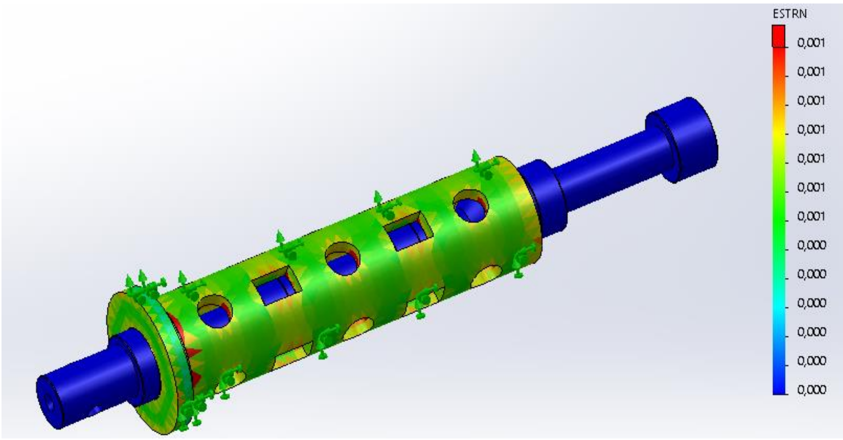

Fig. 4b. Spool-sleeve strain values (75 °C).

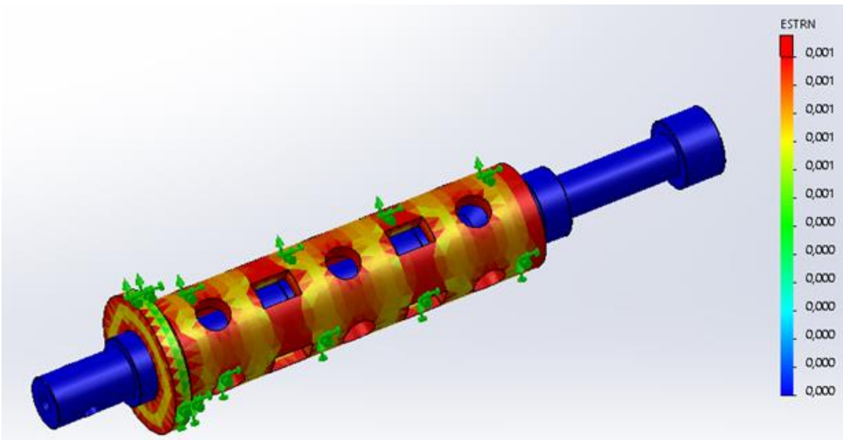

Fig. 4c. Spool-sleeve strain values (100 °C).

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In the analyzes made, it was observed that the stress value for the 50 ºC temperature operating condition was far below the yield value of the material. When a temperature of 75 ºC is applied, the stress values begin to approach the material yield point with the notch effect on the edges of the circular and special geometric flow zone holes that are only opened. The strain values remained at the 0.001 level in both temperature conditions. For the maximum temperature of 100 ºC, the stress values were found to be very close to the yield limit, especially in the regions where the geometric flow areas create notch effect, and the strain value was in the range of 0.001-0.002 only in these regions, and generally around 0.001 in the sleeve-spool assembly. According to the results of the analysis, it was seen that with the geometric dimensions of the design, a tolerance value of 0.001 could be achieved up to a temperature value of 100 ºC, and it was decided that the design would be appropriate and the production would be made according to these values. When the cross-sectional image of the strain analysis result (Figure 5) of the designed sleeve-spool structure for the temperature value of 100 ºC is examined, it is seen that the strain values in the sleeve region are in the order of 0.001, while the spool region is below this value in the range of 0.0001-0.001, therefore the internal structure of the spool is filled with material and is less affected of the temperature. It has been found that it is is suitable for the desired sensitivity.

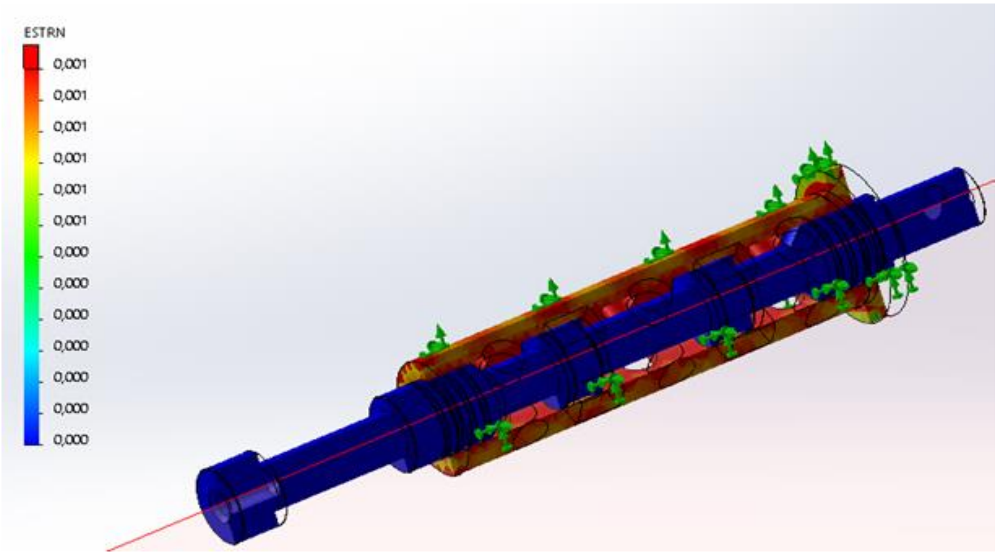

Fig. 5. Cross-section view of spool-sleeve strain values (100 °C).

Another problem related to the operation of servo and proportional valves in the aviation industry is the particulate matter contained in the hydraulic oil and the particle accumulations formed by these substances disrupt the orifice geometry and cause unwanted openings or blockages throughout the stroke. This prevents the required pressure, flow and proportional control of the valve. Although it is recommended to use oils that comply with specially filtered standards in the systems, this issue cannot be taken into account in the places of use and appropriate hydraulic oils are not used. For this reason, another feature desired from the developed valve is to prevent the accumulation of unwanted particulate matter in the orifice area. For this purpose, the desired hydraulic oil is specially turbulent to move. In the analyzes made, a 3D simulation study was carried out. In Figure 6, the cross-sectional view of the valve flow region is given in 3D and schematically. The hydraulic oil, which is the system fluid, enters from the P line and passes through the orifice opening to the A line.

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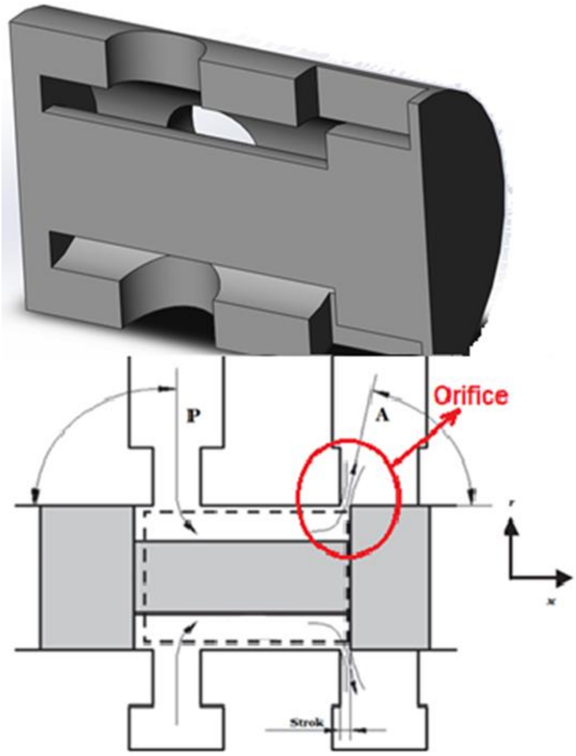

Fig. 6. P-A line spool-sleeve flow area.

After the volume structure of the flow region was extracted with Ansys design-modeler, the flow area mesh structure was created. Figure 7 shows the 3D flow area mesh structure. The flow area is divided into 8000 cells. After the prepared mesh structure, k-ε RNG turbulence model was used for simulation studies. The fluid density and the kinematic viscosity have been set to 860 kg/m3 and to 30 mm2/s, respectively. A second-order upwind scheme is used for the space discretization of the momentum and energy equations in the simulations.

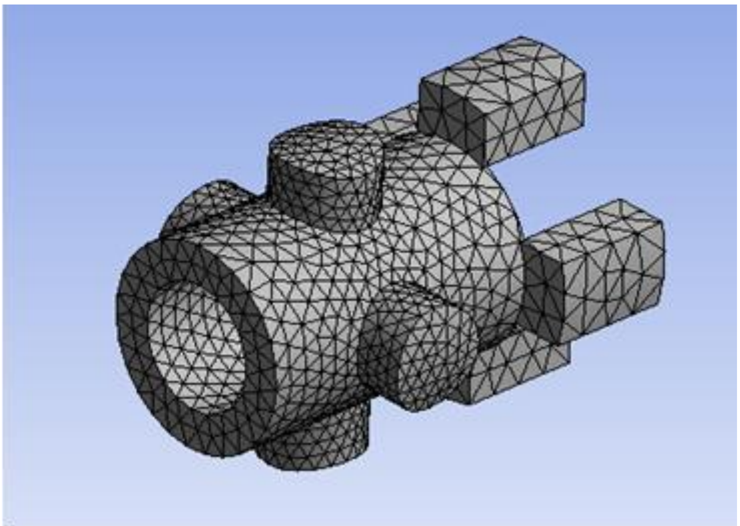

Fig. 7. 3D Mesh structure of the flow area between the P-A line.

After defining the initial boundary conditions of the simulation studies, 300 iterations were performed for all of the calculations. In Figure 8, residuals values for each iteration are given for 0.2 mm orifice calculations. Similar results were seen for 0.6 and 1.2 mm orifice calculations too. When Figure 8 is examined, it is seen that after 50

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iterations, the residuals values almost do not change, that is, convergence can occurs. This means that the selected iteration number is quite sufficient.

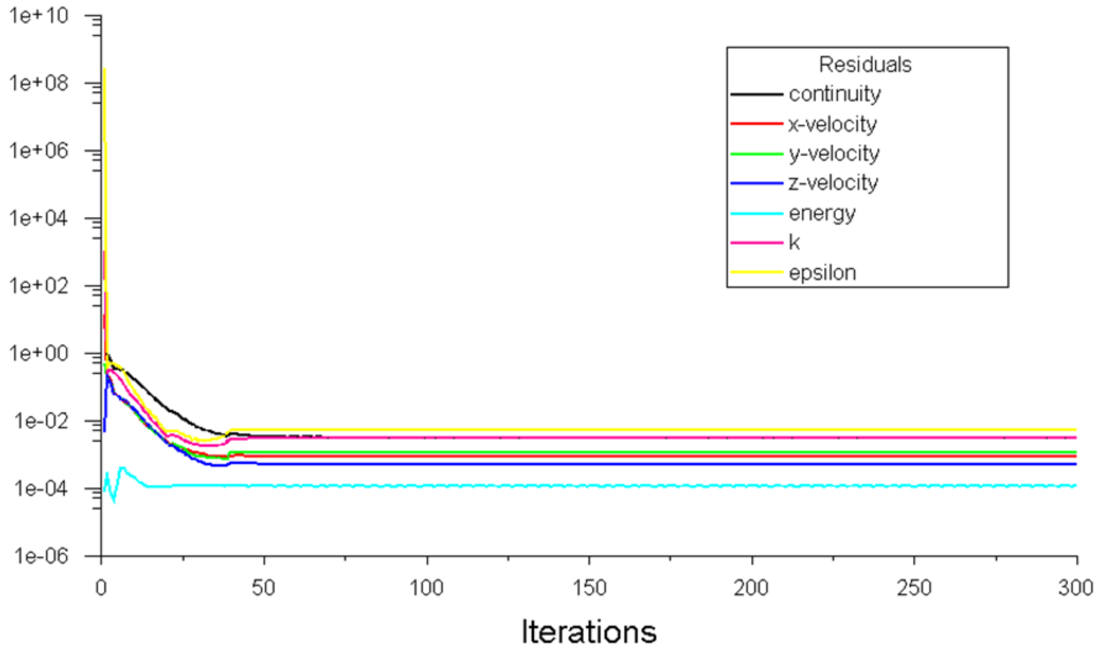

Fig. 8. Sample of ANSYS iteration residuals (for 0.2 mm stroke simulation).

In the analysis, velocity streamlines obtained at 35 bar pressure difference between P and A lines are given in Figure 9a, 9b and 9c for 0.2, 0.6 and 1.2 mm spool stroke movement, respectively. In addition, hydraulic flow turbulent kinetic energy distributions for 0.2, 0.6 and 1.2 mm orifice openings are given in Figure 10a, 10b and 10c. It has been observed that the highest velocity value at 35 bar pressure difference is 337 m/s, this value decreases with increasing orifice opening and reaches 112 m/s velocity at 1.2 mm orifice opening. These flow rates form the jet-flow structure on valve spool-sleeve.

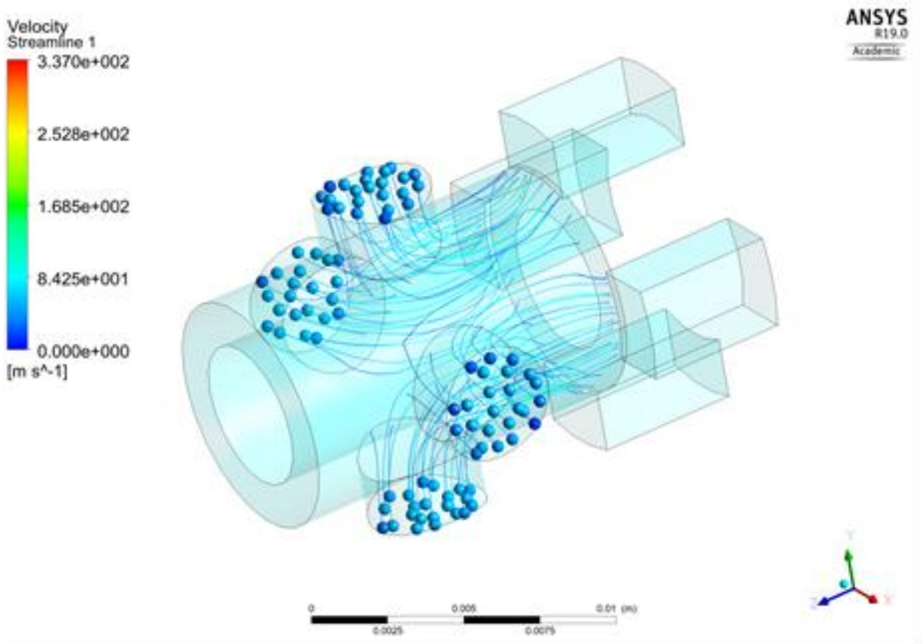

Fig. 9a. Velocity streamlines of flow area (0.2 mm stroke).

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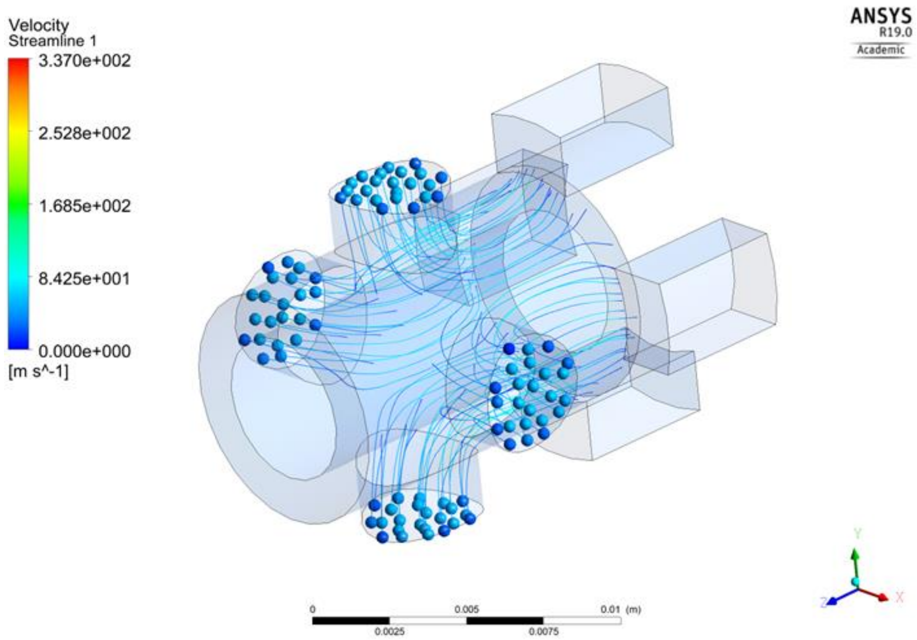

Fig. 9b. Velocity streamlines of flow area (0.6 mm stroke).

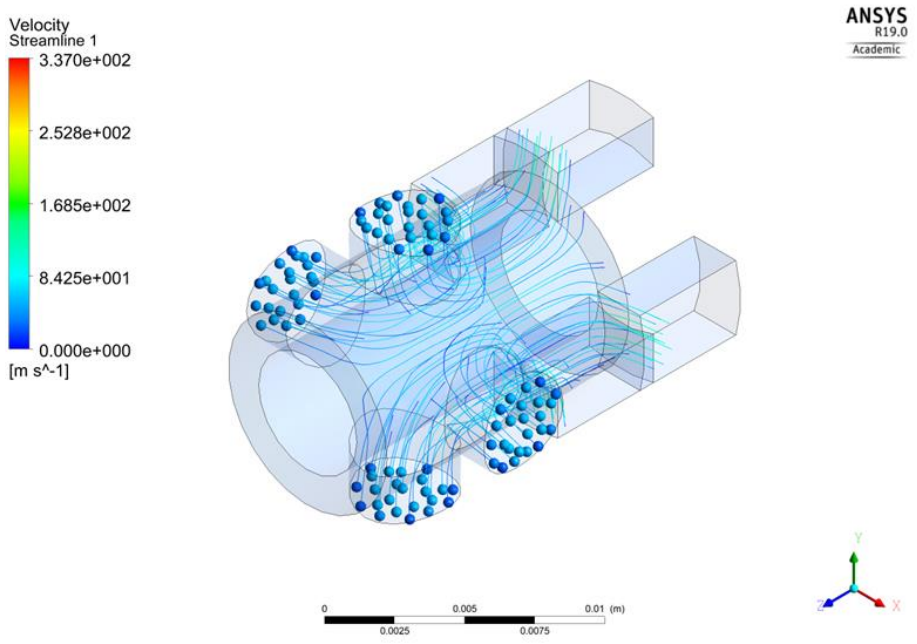

Fig. 9c. Velocity streamlines of flow area (1.2 mm stroke).

In addition, according to the analysis performed, it has been observed that the vertical cross-section spool orifice structure provides sufficient turbulence formation, especially around the orifice structure, from the smallest stroke distance (0.2 mm) to the largest value (1.2 mm). Thus, with the turbulent flow structure that occurs, sufficient movement is provided to disperse the particulate matter and the accumulation of particulate matter can be prevented in the system operation.

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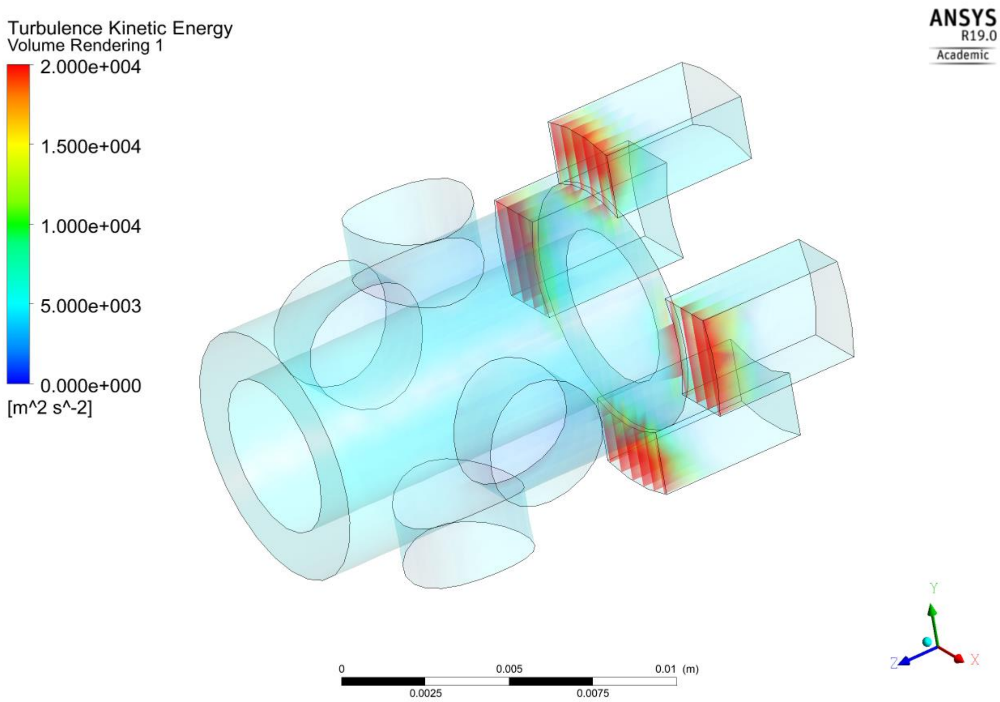

Fig. 10a. Turbulance structure of flow area (0.2 mm stroke).

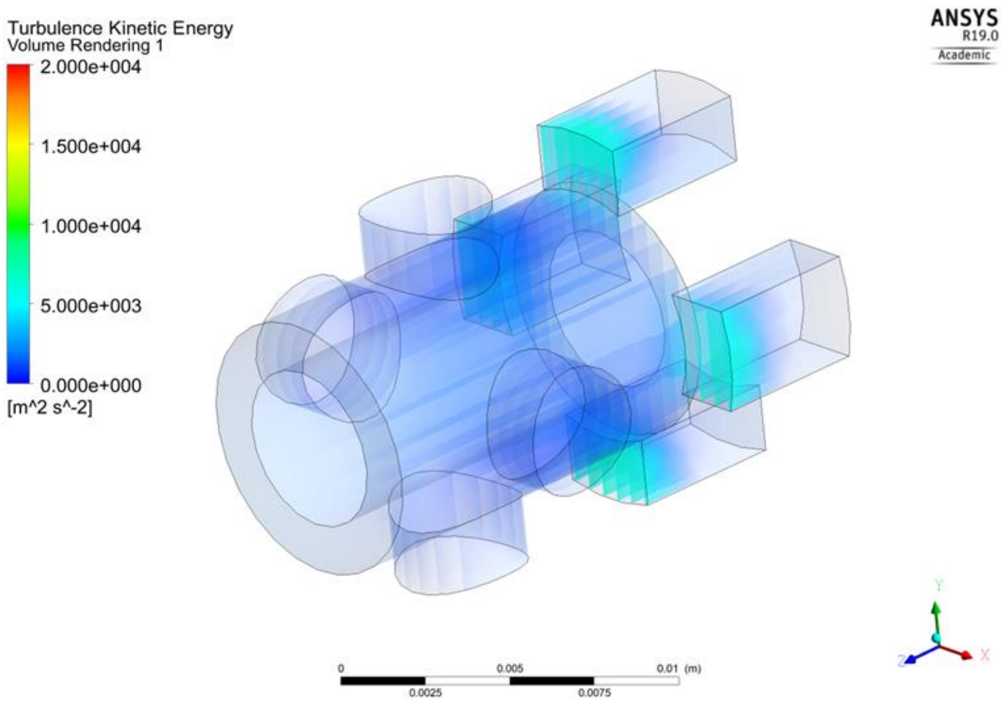

Fig. 10b. Turbulance structure of flow area (0.6 mm stroke).

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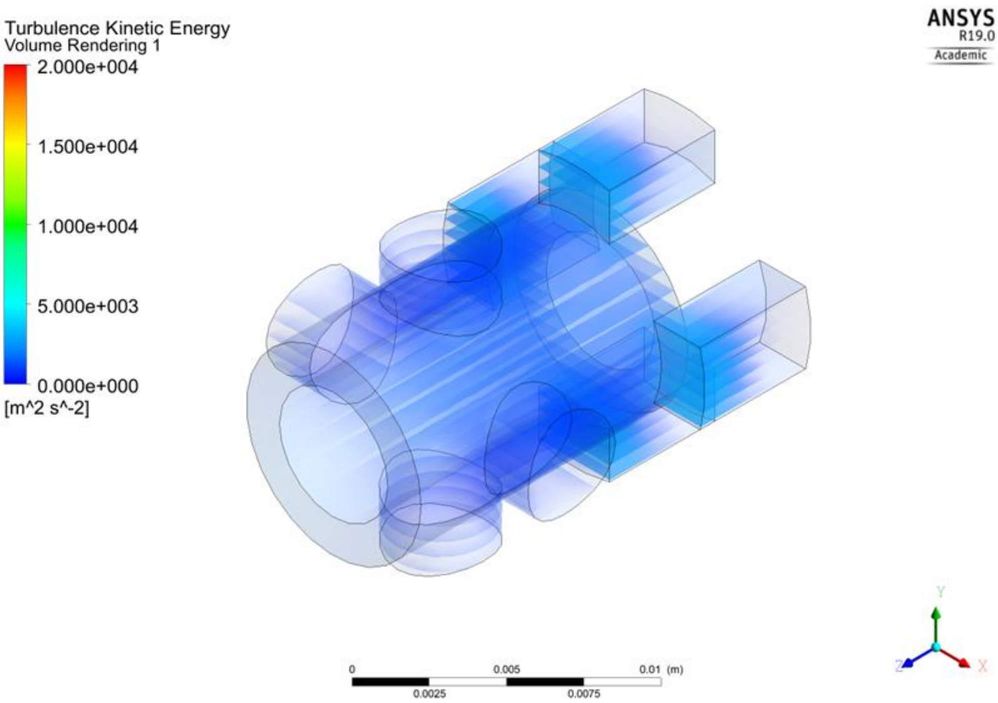

Fig. 10c. Turbulance structure of flow area (1.2 mm stroke).

4. Conclusion

This paper provided a numerical investigation of the thermal behavior of servo proportional valve spool-sleeve structure and hydrodynamic flow characteristic of valve orifice. Temperature values of 50, 75 and 100 °C were selected in the simulations carried out, and the orifice spool opening was 0.2, 0.6 and 1.2 mm.

The optimum operating temperature for hydraulic valves with servo characteristics is 70 °C, and there is no movement problem between the spool-sleeve at 75°C operating conditions. However, in the case of 100 °C temperature, it is clear that excessive friction and movement difficulty will occur due to strain on the spool-sleeve structure of the valve. For this reason, servo valves with precision manufactured spool-sleeve structure must be protected from excessive heat.

Another challenge for servo valves, which is the accumulation of pollutant particles, leading to orifice clogging and orifice geometry deterioration, can only be prevented by providing sufficient turbulence structure and dispersing the particles. In the flow simulations, it is seen that there is sufficient turbulence kinetic energy in all 0.2, 0.6 and 1.2 mm stroke openings, so the accumulation of particulate matter can be prevented.

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