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The Effect of Clearance on Energy Dissipation for the Roots Power Machine Based on Low-Quality Energy Recovery

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1.Introduction

With increasing population, rapid industrialization and increase in comfort and living standard of the people, the demand and consumption of energy is rapidly increasing. Energy and energy utilization technologies are paying more and more attention to meet the energy demands and reduce environmental pollution and greenhouse gas emissions. In addition to the application of renewable resources such as solar energy and wind energy [1], industrial waste heat was used to improve energy utilization. [2] The leftover heat after combustion process or any chemical or thermal process is known as waste heat as it is usually exhausted to the environment. The heat wasted in the industrial process accounts about 20–50% of the input heat. In some cases, the recovery of waste heat can improve the energy efficiency of the system about 10–50% [3]. Low grade heat and waste heat recovery technology not only improve the efficiency of the system but also mitigate the risk of future climate change and reduce energy cost [4–6]. The type and design of expander is the key to the performance, efficiency and cost of low-quality waste heat recovery system. At present, the existing waste heat conversion machinery mainly includes scroll type, screw type, steam turbine type, etc., which meet the needs of some waste heat recovery technology systems [7-12]. However, it is limited by the quality of low-quality steam waste heat resources. As a potential waste heat conversion machine, roots power machine is a kind of a positive displacement expander in which the working fluid pressure is decreased by increasing its volume.

As the heart of waste heat power generation device, the roots power machine plays a key role in the power generation efficiency of low-quality waste heat. It is designed to deliver maximum efficiency. This is only possible if all the associated losses are kept to a minimum. Some research results on the effect of clearance on volumetric fluid machine have been published [13-18]. Li et al. [13] studied the influence of root clearance of axial flow pump on mechanical energy dissipation using numerical simulation and entropy production methods. It found that the leakage flow in the root clearance led to the distortion of the impeller's flow pattern, and the indirect dissipation rate and overall dissipation of the impeller increased with increasing root clearance radius. Sun et al. [14] conducted particle image velocity measurement (PIV) tests using a microscopic lens and phase-lock technology, and obtained the velocity field around the tip gap in an optical Roots blower. They established the three-dimensional unsteady CFD model of the Roots blower with the dynamic grids, and predicted the gap flow under the same operating conditions. Sonawat A. et al. [15] studied the radial clearance and axial clearance of the torsion rotor of PDT by using computational fluid dynamics (CFD), and developed a mechanism to qualitatively and quantitatively analyse and calculate the leakage losses. The results showed that leakage loss caused a slight reduction in the performance of PDT. Andres R. et al. [16] used numerical simulation to establish a screw compressor model including radial clearances and axial clearances, and studied the sensitivity of the change of housing clearances. The results showed leakage flow had severe impact on the compressor performance. Wang et al. [17] tested and discussed its shaft efficiency, volumetric efficiency and gas consumption rate by manufacturing three prototype single screw expander with different clearances. The experimental results indicated that the single screw expander with medium clearance had the best overall performance, which may be further improved by optimizing its configuration. Song et al. [18] proposed a three-dimensional numerical technique available for modelling the radial leakage flows through the axial clearances at the tip and root of scroll wrap. They investigated the radial leakage flow patterns of both axial clearances, and revealed asymmetrical distribution of the radial leakage flow through the axial clearances at both sides of working chambers. They also comparatively discussed leakage flow difference between the top and bottom axial leakage clearances, and analysed the effects of radial leakage on the flow fields in the working chambers. The tip clearance is always provided to ensure that the blade tip of the roots power machine do not get damaged by hitting the casing. Although tip clearance is of the order of few millimetres, but its influence on the overall performance of the roots power machine is very significant. It causes the disturbance of the internal flow field, and causes the leakage flow. This leakage flow influences the main stream flow, and causes generation of turbulent eddies and vortices which causes loss of energy in the flow. Also, it does not contribute to any output power generation by the roots power machine.

The present work makes an effort to demonstrate the effect of tip and radial clearance on the overall performance of the roots power machine using Computational Fluid Dynamics (CFD) and experimental studies. Leakage losses through the clearances play a significant role in deciding the overall performance of the roots power machine. The present work tries to illustrate sensitivity of tip and radial clearance in influencing the performance of the roots power machine and the contribution of leakage flowrate in the total flowrate for different clearance gaps.

2. Numerical modelling

The numerical modelling was done by solving the unsteady and incompressible Reynolds-averaged Navier-Stokes (RANS) and the continuity equations using finite volume approach. In this paper, three-dimensional solid modelling of the roots power machine was carried out. The 3D modelling and the schematic view of the roots power machine with relevant boundary conditions is shown in Figs. 1 and 2. The key dimensions of the base design of the roots power machine are listed in Table 1. The roots power machine consisted of two identical lobe shaped rotors rotating in opposite direction to each other under the influence of applied differential pressure (ΔP). Initially, the tip and radial clearance was fixed to 0.2 mm for each rotor and later it was sequentially varied in the range of 0.2-0.5 mm. Radial clearance is defined as the clearance gap between rotor and rotor tip in the radial direction and tip clearance is defined as the clearance gap between the rotor and casing as shown in Fig. 3, a and b. It should be noted that the diameter of the rotors was 60 mm and their width along the span was 100 mm.

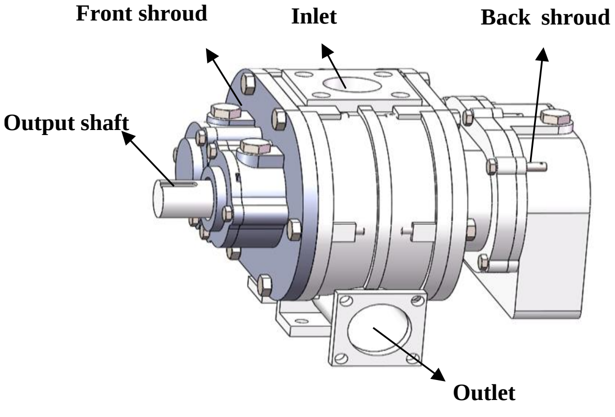


Fig. 1 3D view of the roots power machine

The mesh was generated in the entire fluid domain using FLUENT-ANSYS Workbench. Special attention was concentrated to generate fine grids in the regions susceptible to significant flow interactions like the clearance, interface and the near wall region as shown in Fig. 4. To capture the details of fluid flow phenomenon, transient simulations were performed using moving mesh with the mesh deforming at every single degree rotation of the rotors.

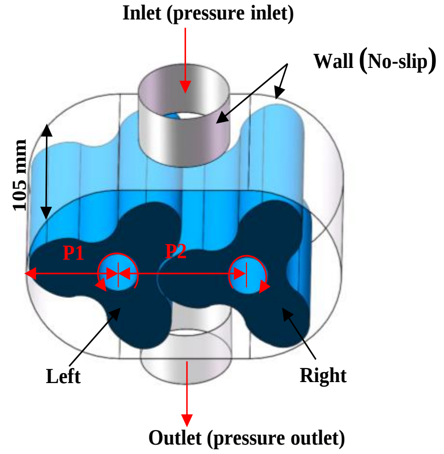


Fig. 2 3D view with boundary conditions

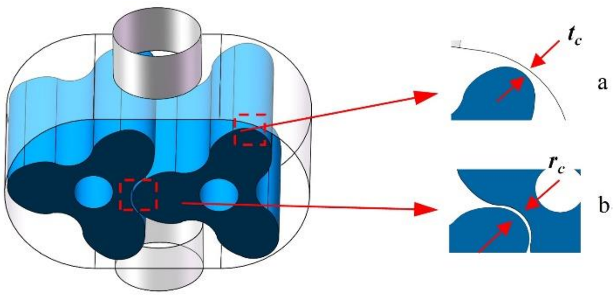


Fig. 3 View of clearances (a) tip and (b) radial

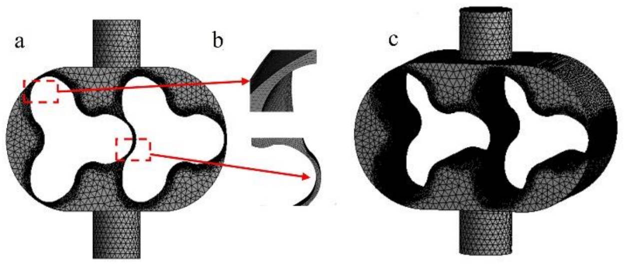


Fig. 4 View of generated mesh (a and b) Sectional view (c) - zoomed view

The RKG $k-epsilon$ model is adopted to make the simulation results more accurate, considering the rotation of the rotor and the curvature effect of the casing. The model adds conditions to the ε equation, which improves the accuracy of flow prediction, and it is also more accurate for flow predictions in small gaps.

Set the parameters in the flow field model. The working fluid was steam. To ensure the reliability, accuracy and convergence, the governing equations were iterated until the root mean square (RMS) residues of the dependent variables dropped below 10^{-4}.

The mechanical efficiency is defined as the ratio of actual output power to the theoretical output power and is represented by:

$$Mechanical\ efficiency(\eta_m)=\frac{actual\ output\ power}{theoretical\ output\ power}.$$

The total mechanical efficiency is defined as the ratio of actual output power to the theoretical output power and is represented by:

$$Total\ Efficiency(\eta) = \frac{output\ mechanical\ power}{Input\ air\ pressure\ power} == \frac{T * \omega}{P_1 * Q},$$

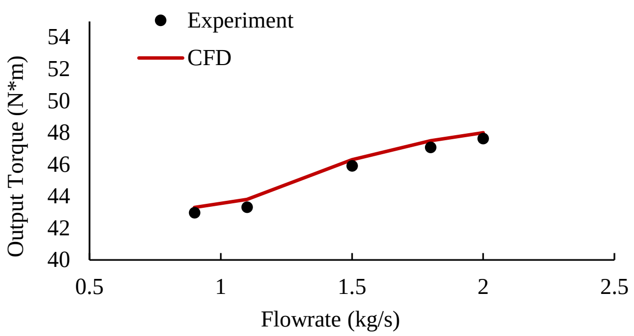
where: T is the torque, N∗m; ω is the rotor's rotation speed, rpm; P_1 is the inlet steam pressure, Pa; Q is the steam flow, m^3/s.

3. Results and discussion

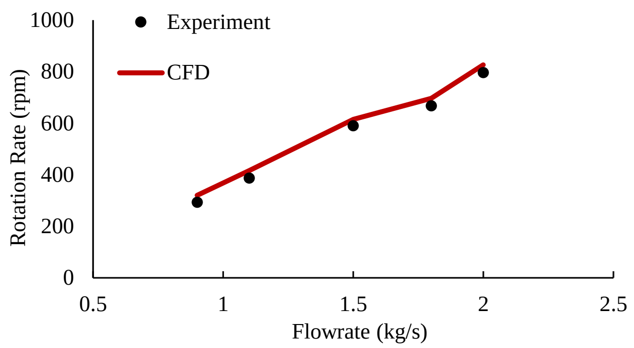
3.1. Validation

The reliability of the obtained CFD results was determined by the corresponding experimental data. Experimental tests were conducted in our laboratory on the design of the roots power machine having moderate clearances, i.e., tip clearance (t_c) of 0.4 mm and radial clearance (r_c) of 0.2 mm and the obtained test data was compared with the CFD results as shown in Figs. 5, a and b. A good agreement was obtained between both the studies proving the reliability of our Computational Fluid Dynamics (CFD) approach.

As shown in Fig. 5, a, the prediction of torque and speed by CFD closely resembled with the experimental results shown in Fig. 5. The maximum error between the predicted speed and torque was less than 0.5%. The small deviation between the experimental results of CFD prediction of torque and speed were because CFD studies did not account for the actual mechanical losses, such as transmission, coupling, etc.



a



b

Fig. 5 Validation of CFD results with the experiment (a and b)

The schematic view and the actual picture of the developed test facility are shown in Figs. 6 and 7. All the instruments used for the experiment mainly includes the pressure gauges, temperature sensors, flowmeter, torque sensor, eddy current brake etc. The output shaft of the roots power machine is connected with torque sensor and eddy current brake to study the power performance of the roots power machine more accurately. The eddy current brake replaced the previous generator load and had a stronger protective effect on the test platform. The eddy current brake had a wider range of torque adaptation, and did not cause damage to the device due to instantaneous over-torque. The torque sensor monitored the operating torque and operating speed of the roots power machine in real time, and transmitted the data to the controller. The controller adjusted the intake pressure by adjusting the opening of the electric regulating valve, so that the roots power machine achieved steady-state operation.

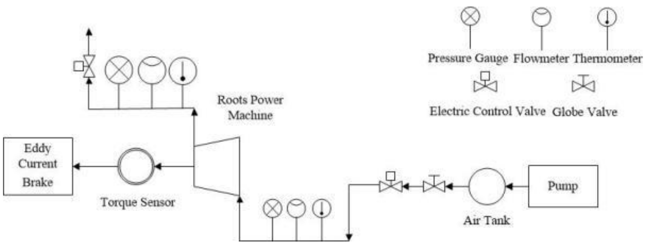
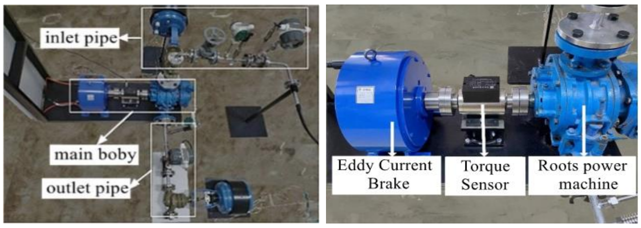


Fig. 6 Schematic view of test facility



a

b

Fig. 7 View of the test setup (a); Power measuring instrument and Eddy current brake controller (b)

Experimental studies were conducted in our laboratory for three models of the roots power machine each having different values of tip clearance gap t_c and radial clearance gap r_c. From the experimental studies, it was observed that as t_c and r_c increased, the rotation rate and output torque of the roots power machine decreased. It can be seen from Figs. 8 and 9, at t_c and r_c=0.2 mm, the rotation rate and output torque were the highest for all flowrate. As r_c increased to 0.4 mm keeping t_c same for the second model, the rotation rate and output torque decreased, indicating smaller the rotation rate and output torque at all corresponding flowrate. For the third design with t_c and r_c=0.4 mm, the rotation rate and output torque are the smallest. This was due to the flow leakage at the higher t_c and r_c. The increase in flowrate leakage with an increase in clearance gap was due to the fact that the overall clearance area and hence the associated clearance volume increased. But this increased flowrate leakage did not favour the performance of the roots power machine. Figs. 8 and 9 clearly highlighted the fact that as the clearance gap increased, the generated torque and rotation rate were affected. Hence the clearance gap had an impact on the performance of the roots power machine.

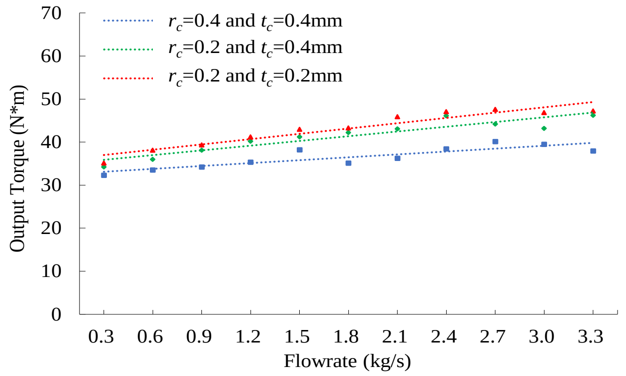


Fig. 8 Output Torque of roots power machine at different tip and radial clearance values

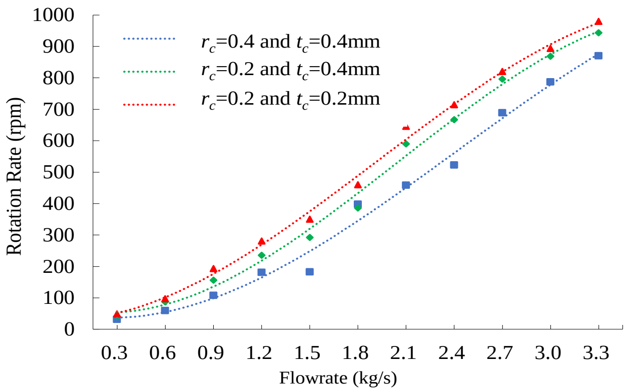


Fig. 9 Rotation Rate of roots power machine at different tip and radial clearance values

3.2. Parametric study on the sensitivity of the tip clearance and radial clearance

From the experimental study with three models having different t_c and r_c, it was demonstrated that the values of clearance gaps significantly influenced the performance of the roots power machine. This paved way to find which clearance (t_c or r_c) was more pivotal in influencing the performance of the roots power machine. Hence a parametric study was done using CFD approach to find the answer of this question. Thereafter, keeping t_c fixed to 0.2 mm, the value of r_c was varied from 0.2-0.5 mm and then keeping r_c fixed to 0.2 mm, the t_c was also varied in the same range from 0.2-0.5 mm. Fig. 10 shows the outcome of this parametric study. The non-uniformity of the contact area encountered by the fluid as it entered the rotor caused abrupt and instantaneous fluctuations in torque and power. Therefore, the output power changed when r_c is 0.45 mm. The fluctuation in the flowrate were the result of leakage flow, and the gap changed continuously with each degree of rotation of the rotors. It can be seen from Figs. 10 and 11 that for clearance gap values between 0.25-0.5 mm, the r_c showed slightly higher sensitivity than the t_c as the clearance gap increases, the output torque and output power decrement are slightly higher than t_c. In the range of 0.2-0.25 mm, the t_c showed slightly higher sensitivity than the r_c. As can be seen from Fig. 14, according to the volume area of the calculated gap, the volume of the tip clearance is slightly larger in the range of 0.2-0.25 mm, so the corresponding leakage loss is higher in this range. In the range of 0.25-0.6 mm, the area of radial clearance is larger than that of tip clearance, resulting in higher corresponding leakage loss. Nonetheless, the most interesting fact worth noting was the contribution of the leakage flowrate in the inlet flowrate passing through the roots power machine in the chosen range of clearance gaps.

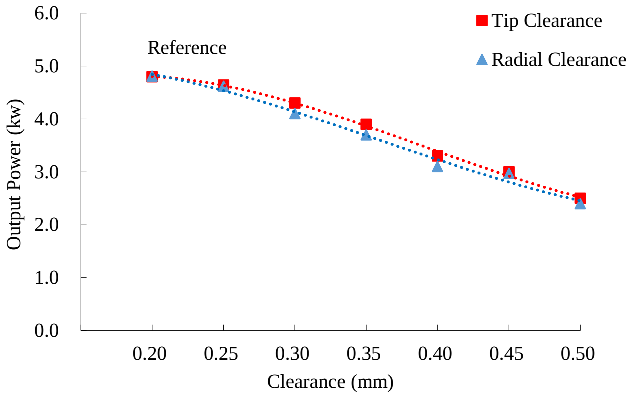


Fig. 10 Sensitivity analysis of tip and radial clearance to Output Power

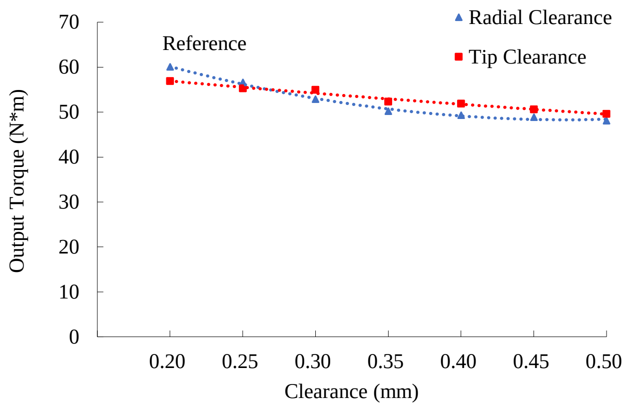


Fig. 11 Sensitivity analysis of tip and radial clearance to Output Torque

From Fig. 12, it can be seen that for r_c=5 mm, the leakage flowrate was 25.12% of the total flowrate passing through the roots power machine. While from Fig. 13 at t_c=0.5 mm, the leakage flowrate was 24.11% of the total flowrate. Strictly understanding, almost 25% of the total flowrate was simply lost through the small clearance gaps and thereby causing leakage losses. This showed the significance of clearance gap value selection for the roots power machine. As the values of the t_c and r_c were reduced, the contribution of the leakage flowrate (or leakage losses) reduced. For r_c=0.2 mm, the leakage flowrate was 5.04% of the total flowrate whereas at t_c=0.2 mm, it was 5.02%. The reason for this swing in sensitivity was explained by the calculation of the clearance volume from the CAD geometry.

From Fig. 14, it can be seen that in the range of 0.25-0.5 mm, the radial clearance volume was slightly higher than the tip clearance volume, thereby causing slightly higher leakage losses. Where as in the range of 0.2-0.25 mm, the tip clearance volume was slightly greater and hence the corresponding leakage losses were higher in this range. Another interesting thing worth nothing was the fact that at t_c and r_c=0.5 mm, the clearance volume was just close to 5% of the total roots power machine volume (sum of the clearance volume and displacement volume,) as seen in Fig. 15. But it accounted for almost 30% of the total flowrate through the roots power machine. This further ascertained the significance of clearance gaps values for the roots power machine. It can be safely concluded from this study that the clearance gaps should be kept to a minimum value to have higher performance.

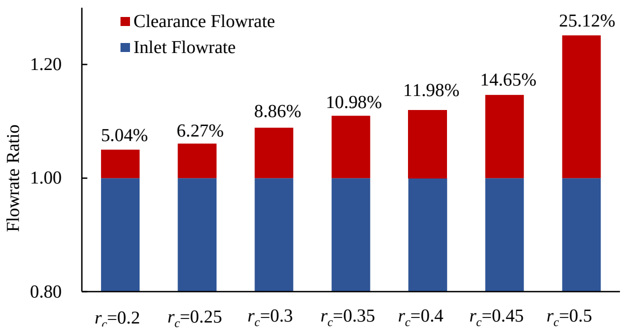


Fig. 12 Variation of flowrate ratio with different radial clearance values

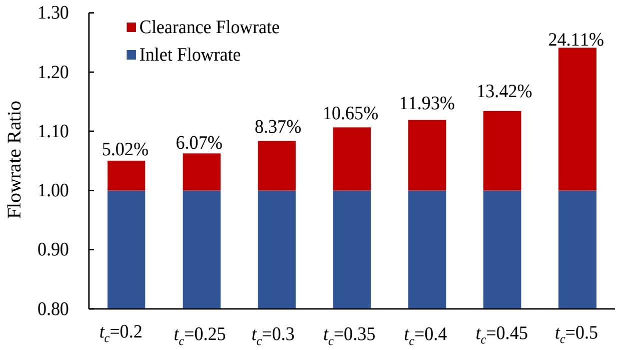


Fig. 13 Variation of flowrate ratio with different tip clearance values

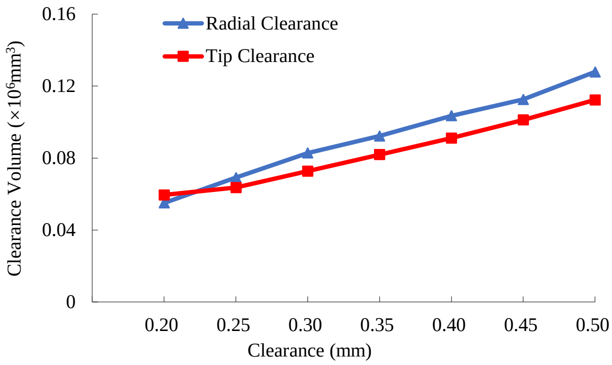


Fig. 14 Variation of clearance volume with clearance

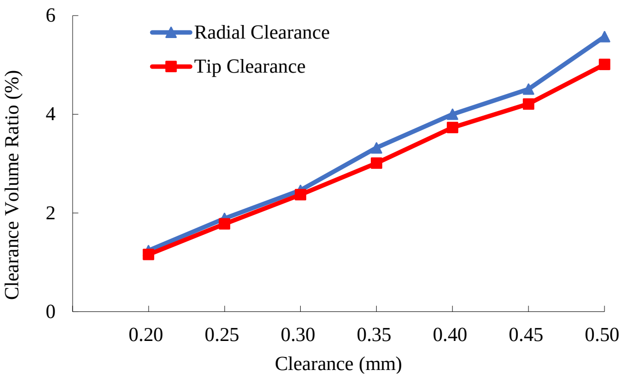


Fig. 15 Variation of clearance volume ratio with clearance

After sensitivity analysis, the effect of reduction in tip and radial clearance on the performance of the roots power machine was analysed. Leakage of flow through the clearances between the rotor and the casing is very significant in deciding the overall performance of the roots power machine. Hence, apart from η_m, η_v is also very important. η_v can quantify the leakage losses and effectiveness of the roots power machine based on leakage flowrate. It should be noted that both the tip and radial clearances s_c were equal for a given case and their variation was also constant. Initial tip and radial clearance gap s_c for the roots power machine was 0.2 mm and was increased in a sequential manner to 0.5 mm. As shown in Fig. 16, the gap decreases from 0.5 mm to 0.2 mm, and the η_m and η_v show considerable increase. This can be attributed to the fact that the losses arising due to the leakage of flowrate through the clearance regions were significantly reduced with reduction in clearance gap. The maximum η_v was 91.877 % for s_c =0.2 mm.

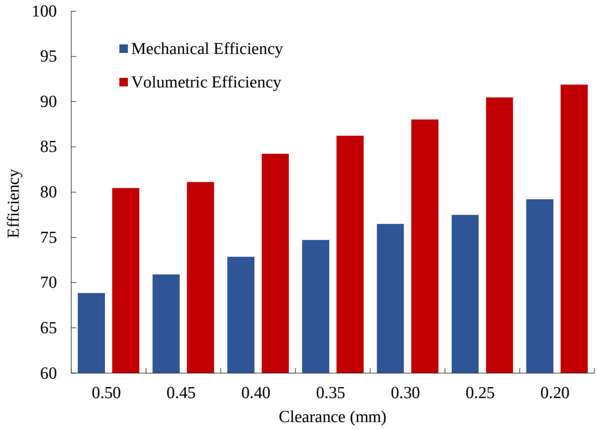
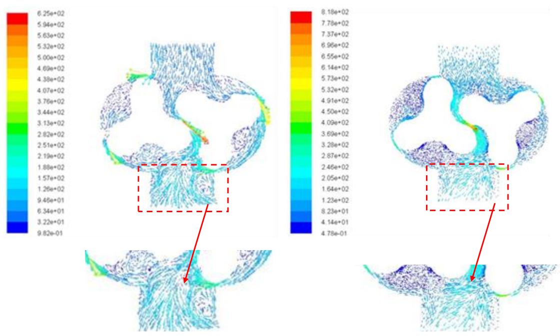


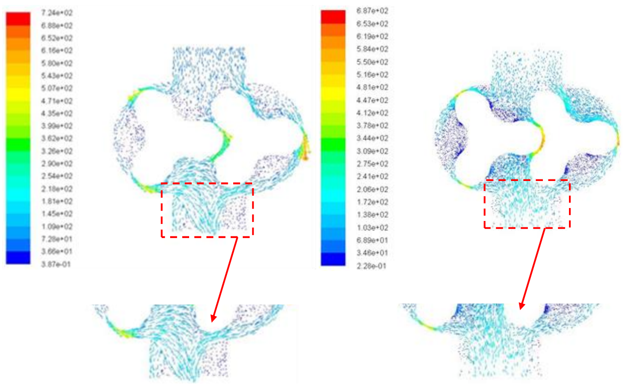
Fig. 16 Comparison of efficiencies at different clearances

To qualitatively observe the effect of leakage flow, as shown in Figs. 17 and 18, compared with the design with s_c = 0.2 mm, the radial clearance area with s_c = 0.5 mm has a higher speed, which proves that there is a higher leakage flowrate through these areas. A similar phenomenon is observed in the tip clearance region along the span wise direction between the rotor and casing clearance. It should be noted that the flowrate through any volume is the product of the cross-sectional area and the velocity of the fluid through that region. For s_c = 0.5 mm, both the cross-sectional area in the clearance gap and velocity were higher indicating greater leakage flowrate through that volume as compared to s_c =0.2 mm, as shown in Figs. 17 and 18. Hence, greater leakage losses for s_c =0.4 mm and reduced performance as compared to lower s_c values.



s_c =0.5 mm s_c =0.2 mm

Fig. 17 Streamline contours for 0° rotor rotation angle



s_c =0.5 mm s_c =0.2 mm

Fig. 18 Streamline contours for 45° rotor rotation angle

The flow downstream of the rotor was very complex. This was due to the mixing of rotor-rotor leakage flowrate, rotor tip leakage flowrate and main flowrate, resulting in two different vortices. It was found from Figs. 16 and 17 that the mixing of leakage flow and main flow had a greater disturbance on s_c = 0.5 mm compared with s_c = 0.2 mm. The flow downstream of the rotor is more affected by the rotor-rotor leakage flowrate. These effects are caused by the induction effect caused by the higher leakage flowrate speed in the rotor-rotor clearance gap, and were limited in a small area downstream of the rotor.

4. Conclusion

The influence of tip clearance and radial clearance on the overall performance of roots power machine was expounded, and the fluid flow characteristics were examined by experiment and CFD. In addition, parametric studies were carried out to find out the sensitivity of these clearances in affecting the overall performance of the roots power machine. The effect of reduction in clearance gap was also examined using CFD approach. It can be concluded that:

1. The leakage losses through the clearance significantly influenced the performance of the roots power machine. Hence, the clearances should be kept to the minimum values. The size of the clearance gap depends on various factors. For our practical application, the lowest possible value of the clearance gap was 0.2 mm.

2. The increase of leakage losses due to the increase of clearance significantly affected the generation of output torque and rational rate, thus reducing the overall efficiency. For the clearance gap in the range of 0.2-0.25 mm, t_c was slightly more sensitive in influencing the performance of the roots power machine, while r_c was instrumental in the range of 0.25-0.5 mm. This was due to the higher clearance gap volume in the corresponding gap range.

3. The clearance gap decreased from 0.5 mm to 0.2 mm, resulting in the increase of η_m and η_v by 10.368 % and 11.423 %. Both these increments are due to the reduction in leakage of flowrate.

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THE EFFECT OF CLEARANCE ON ENERGY DISSIPATION FOR THE ROOTS POWER MACHINE BASED ON LOW-QUALITY ENERGY RECOVERY

S u m m a r y

As a new type of waste heat conversion machine, the roots power machine can convert low-quality waste heat resources that are difficult to use into mechanical energy. In order to study the influence of tip clearance and radial clearance on the roots power machine, experimental studies were conducted with the roots power machine having different combination of tip and radial clearances and their influence on the performance of the roots power machine was examined. A parametric study was undertaken using CFD to find the sensitivity of these clearances in influencing the performance of roots power machine in the range of 0.2-0.5 mm. From the analysis, it was inferred that radial clearance was sensitive for clearance range of 0.25-0.5 mm and tip clearance in the range of 0.2-0.25 mm. Reduction in clearance from 0.5 mm to 0.2 mm caused an increase of 10.368 and 11.423% in mechanical and volumetric efficiency respectively.

Keywords: renewable energy, computational fluid dynamics, the roots power machine, clearance sensitivity, leakage losses.

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