Structure of turbulent natural convection in a heated rapidly rotating inter-disk cavity with near-axis heat sinks

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Abstract. The paper presents the results of implicit LES numerical analysis of natural convection developing in a rapidly rotating inter-disk cavity with the width-to-radius aspect ratio equal to 0.13. The convection under study is developed under conditions of a prescribed temperature distribution over the disk surfaces and heat removing action of two near-axis volume sinks of a proper intensity. The thermal conditions are defined on the base of experimental data available in the literature for the prototype case of mixed-convection flow in a cavity heated from the side of the disk surfaces with axial throughflow of cooling air. The computations were carried out for the Ekman layer equal to $0.28 \cdot 10^{-4}$, if evaluated with the cavity width. Using the closed-cavity model with near-axis heat sinks, principal features of the flow structure and heat transfer, revealed previously for the prototype case of mixed convection have been reproduced successfully, including formation of a pair of global cyclonic/anticyclone vortices and a cold flow core of nearly constant temperature. It is shown also that each near-disk shear layer can be subdivided into a relatively thin highly gradient “internal” Ekman-type layer and a much thicker “outer” layer, which thickness is of the same order as the thermal layer thickness. For the case considered, groups of elongated regular structures occur within the outer layer that can be detected by analyzing the low-speed fluid motion in the axial direction. Further studies are needed to reveal physical reasons of occurring these structures.

1. Introduction

As typical components, the drum-type rotor of a compressor of a gas turbine engine includes rapidly rotating cavities. In the last compressor stages, the heated during compression air gives off part of its heat to bounding cavity walls. This heat is removed from the walls by turbulent convection formed in the cavity and carried away by the axial throughflow of relatively cold air, which is taken from the intermediate compressor stage and goes to cooling the turbine disks and blades. To accurately predict the thermal state of compressor disks, extended knowledge of localized heat transfer in ventilated cavities is critical.

The problems of mixed convection in rapidly rotating annular cavities are very complex [1]. Interest in research in this area has emerged in the 1990s, when first systematic experiments were fulfilled to study
the axial throughflow effect on the integral and local heat transfer in single annular cavities under various conditions of wall heating [2–6]. Further experiments were carried out mainly due to the results of local heat transfer measurements [7–12] and has not included extended information about 3D unsteady velocity and temperature fields that is important for deeper understanding of the fluid dynamics and heat transfer in the cavity.

Applications to this problem of computational methods based on the RANS (Reynolds-averaged Navier-Stokes) approach [13–15] have shown generally their inconsistency. At present, significant progress in this area can be achieved using eddy-resolving approaches [8, 16–21]. The highest expectations are associated with the application of the high-precision DNS method, as well as with the Implicit LES (ILES) technique, where the role of physical dissipation on small scales is replaced by the dissipative properties of the numerical scheme. An initial experience of using the ILES method for simulation of convection in ventilated rapidly rotating cavities is contained in [8, 16, 17, 21].

When using the ILES approach with grids of moderate dimensions, there is a doubt about the sufficiency of grid resolution for adequate transfer of turbulent content from the throughflow zone to the inter-disk area of heated air circulation. This gives motivation to replace the throughflow region with a volume heat sink in the axial convection region. This model eliminates shear mixing layers with small-scale turbulence requiring a strong refinement of the computational grids for high-quality resolution.

In this work, the authors present the results of computations performed with the ILES methods for natural convection in a rapidly rotating inter-disk cavity in the presence of volume heat sinks placed in the cavity center. The geometrical and thermal conditions are defined on the base of experimental data available in [4] for the prototype case (figure 1a) of mixed-convection flow in a cavity heated from the side of the disk surfaces with axial throughflow of cooling air.

2. Case definition

The problem of turbulent natural convection of air in a rapidly rotating heated inter-disk cavity is considered (figure 1b). According to [2–4], the outer radius of the cavity, \( b \), is set 0.4845 m, and the cavity width \( s = 0.065 \) m. The origin of the coordinate system is placed in the center of the cavity at the axial middle (central) plane.

It is supposed that the disks are heated symmetrically, and the radial distribution of disk surface temperature is same as defined in [2–4] and used in some CFD studies [13, 18, 21]. The peak temperature is 114 °C, and the surface-averaged temperature is \( <T_{\text{disk}}> = 101 \) °C. The shroud surface is treated as adiabatic.

The heat coming from the disk surfaces is removed with two cylinder-form heat sinks positioned in the cavity center (figure 1b). The heat-sink zones are attached to the disk surface \( (z/s = \pm 0.5) \), and the adiabatic condition is imposed at the disk surface at this place. The radius of the heat-sink zones, \( a \), is set to 0.045 m, that corresponds to the inner diameter of the axial tube in the prototype case with axial throughflow. The axial size of the sinks, \( s^* \), is set to 0.3s. With this choice, the predicted large-scale structure of natural convection in the cavity turns out to be similar to that observed in the prototype mixed-convection case. The heat sink intensity is supposed spatially uniform. Therefore, only one free parameter arises to define thermal conditions completely. It is the integral heat rate, \( Q \), removed from the cavity.

The computations on the base of the Navier-Stokes compressible gas equations were carried out at the cavity rotation speed of \( \Omega = 128 \) rad/s that corresponds to the rotational Reynolds number \( \text{Re}_\Omega = \rho_0 \Omega b^2 / \mu_0 = 2 \cdot 10^6 \). Here the characteristic values of the air density, \( \rho_0 \), and viscosity, \( \mu_0 \), are evaluated at temperature of 38 °C as in the prototype case with axial throughflow of cooling air. The integral heat rate \( Q \) is prescribed equal to 266 W. This choice was based on analysis of computational data presented in [18] for Case B (\( \text{Re}_\Omega = 2 \cdot 10^6, \text{Re}_z = 2 \cdot 10^4 \)) studied experimentally in [4].
Figure 1. (a) Scheme of the configuration used in [4] for experimental study of mixed convection in a rapidly rotating inter-disk cavity with axial throughflow of cooling air, (b) scheme of the model for the present numerical simulation of natural convection in a similar cavity with two near-axis heat sinks.

3. Computational aspects

Numerical simulation was carried out using the ANSYS Fluent 19.3 software package. The problem was considered in a reference frame rotating with a constant angular velocity, $\Omega$, on the basis of the perfect gas model with constant values of the dynamic viscosity, $\mu = \mu_0$, and thermal conductivity, $\lambda$; the latter was evaluated via setting the Prandtl number to 0.71.

Figure 2 illustrates the used computational grid, which includes $5.5 \times 10^6$ hexagonal cells. This grid was obtained via translation of a preliminary generated unstructured $x$-$y$ plane grid to 101 points in the axial direction. The points of translation were clustered symmetrically near both disks to achieve a good resolution of the Ekman-type boundary layers developing near the disk surfaces. The grid was clustered to the shroud surface as well.

The solution presented was computed using the QUICK scheme for convective flux evaluation and can be treated as an eddy-resolving solution obtained in the framework of the Implicit LES method.

Time-advancing was performed with the second-order fractional step method (Non-Iterative Time Advancement). The time step was $10^{-4}$ s that provided the Courant number less than unity in the whole computational domain. After a transient period, the flow and heat transfer statistics were gathered for a time corresponding to about 100 revolutions of the cavity.
4. Results of computations and discussion

Figure 3a illustrates instantaneous relative velocity fields in the central axial section of the cavity. A pattern of flow streamlines, which is superimposed on the tangential velocity map, shows that two large-scale vortices develop in the cavity, one of them is cyclonic and the other is anticyclonic. These vortices evolve somewhat in time; however, the general global structure keeps similar and performs an azimuthal relative precession with an angular speed of about $-0.07\Omega$ i.e. controversially to the direction of global rotation. Two points shown at the streamline pattern, $P_1$ and $P_2$, indicate the positions chosen for analysis of typical profiles of relative tangential and radial velocities (given below).

Figure 3b presents an instantaneous distribution of axial velocity over the cavity axial section positioned placed at $z/s = 0.35$. It is seen that groups of elongated structures with different axial velocity sign are resolved in the flow field computed direction. Generally, axial velocities in the given section are almost two orders of magnitude lower than the peak relative tangential velocities. The physical reasons of occurrence of these structures are unclear at the moment. Figure 4 shows that intensity of the axial motion decreases with shifting of the section both to the disk and to the middle plane. A sample of instantaneous axial velocity distributions over a meridional section (figure 4d) points that these distributions tend to be symmetrical with respect to the central plane.
Figure 3. (a) An instantaneous pattern of central-plane streamlines superimposed on the corresponding map of relative tangential velocity values, (b) an instant map of axial velocities in the plane placed at $z/s = 0.35$.

Figure 4. (a)-(c) Instantaneous maps of axial velocities in the planes placed at $z/s = 0.35$, 0.47 and 0.485, correspondingly, (d) an instant distribution of the axial velocity in a meridional section.

A three-dimensional illustration of flow structures developing in the cavity is given in Figure 5, where a system of vortex structures are visualized by Q-criterion isosurfaces and given in combination with a semi-transparency map of axial velocities in the plane positioned at $z/s = -0.35$ i.e. symmetrically with...
respect to the plane taken for the plot in Figure 3b. One can see several axial columns with concentrated vorticity in the flow core, as well as near-disk (symmetrically positioned) vortex structures oriented along the above-discussed structures in the axial velocity distribution.

Figure 6 shows an instantaneous and the time-averaged temperature distributions over a meridional section of the cavity. In the plots, one can see a relatively cold flow “core” and two thermal layers adjacent to the disk surfaces. As a characteristic temperature of the cold core, a value of the section-averaged temperature for the central plane was evaluated that resulted in $<T_{\text{core}}>$ = 62 °C; consequently a characteristic temperature difference $\Delta T = <T_{\text{disk}}>-<T_{\text{core}}>$ = 39 °C. Note also that the whole thickness of the thermal layer does not significantly along the radial direction. Its value can estimated as $\delta_T \approx s/4$.

Figure 5. Pattern of vortex structures visualized with Q-criterion isosurfaces (5000 s$^{-2}$) in combination with a map of axial velocities in the $z/s = 0.35$ plane taken for the same instant.

Instantaneous profiles of relative radial and tangential velocities extracted at points $P_1$ and $P_2$ are presented in Figure 7. At both points, velocity profiles show the presence of the flow core, which is nearly uniform in the axial direction and the near-disk shear layers where the vector velocity turns at a considerable angle. These general features are typical and well known for flows in rapidly rotating cavities [1]. The specific of the case considered consists in pronounced sub-division of the near-disk layer into a relatively thin highly gradient “internal” layer and a much thicker “outer” layer, which thickness is of the same order as the above-introduced for the thermal layer. With the following estimation, one can justify the inner layer is of the Ekman type. Let’s introduce the Ekman number as $\text{Ek} = \frac{\mu}{(\rho_0 \cdot \Omega s^2)} = \frac{(b/s)^2}{Re_\Omega}$. For the case considered $\text{Ek} = 0.28 \cdot 10^{-4}$. A characteristic relative scale, $\delta/s$, of the “classical” Ekman layer is evaluated as $\delta/s = \text{Ek}^{1/2}$. In turn, the whole thickness of the Ekman layer, $\delta_{E_k}$, may be estimates as $\delta_{E_k} \approx 3\delta$. Finally one obtains $\delta_{E_k}/s \approx 0.16$. This estimation is shown at the right plots in Figure 7 by vertical dashed lines.

Figure 6. Instantaneous and time-averaged temperature distributions over a meridional section.
Figure 7. (a) Instantaneous profiles of relative radial and tangential velocities extracted at point $P_1$ (shown in Figure 3), (c) same for point $P_2$, (b) stretched fragments of the point $P_1$ profiles near the disk surface, (d) same for the point $P_2$ profiles.

Figure 8a illustrates instantaneous distribution of the heat transfer coefficient, $\alpha$, over the disk surface. The heat transfer coefficient is calculated using the above-defined characteristic temperature difference $\Delta T$. Radial distribution of the Nusselt number characterizing the intensity of local heat transfer at a current radius $r$ is shown in Figure 8b. This parameter was evaluated as $\text{Nu}_{\text{loc}} = \langle q \rangle r / (\Delta T \lambda)$, where $\langle q \rangle$ is the disk-surface heat flux averaged over time and over angular coordinate. The $\text{Nu}_{\text{loc}}$ distribution obtained looks very similar to that reported in [18] for the prototype mixed convection case (Case B) with the eddy-resolving SAS approach.

Figure 8. (a) Instantaneous distribution of the heat transfer coefficient over the disk surface, (b) radial distribution of the local Nusselt number.
5. Conclusion

Using a vortex-resolving approach of the implicit LES family, numerical simulation of turbulent natural convection in a rapidly rotating inter-disk cavity has been performed. The convection under study was developed under conditions of a prescribed temperature distribution over the disk surfaces and heat removing action of two near-axis heat sinks of a proper intensity. Using this model, principal features of the flow structure and heat transfer, revealed previously for the case of mixed convection in heated cavities with axial throughflow were reproduced successfully, including formation of a pair of global cyclonic/anticyclone vortices and a cold flow core of nearly constant temperature. It has been shown also that each near-disk shear layer can be subdivided into a relatively thin highly gradient “internal” Ekman-type layer and a much thicker “outer” layer, which thickness is of the same order as the thermal layer thickness. For the case considered, groups of elongated regular structures occur within the outer layer that can be detected by analyzing the low-speed fluid motion in the axial direction. Further studies are needed to reveal physical reasons of occurring these structures.

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