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Numerical Simulation of Flow and Heat in Gas Turbine Exhaust Diffuser

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Abstract: Exhaust diffuser is an important member of the turbo machines. This equipment recovers static pressure by reducing the flow rate in gas turbines that increasethe pressure ratio, output work and efficiency of the turbine. This study aims to simulate the fluid flow and heat transfer of the exhaust gas from the turbine and also metal parts of the liner and diffuser because the factors affecting the destruction in the gas turbine exhaust system liners and diffusers are temperature, flow rate and high pressure of the flow passing on them. Reduced lifetime of materials and the creation and growth of cracks in the liner and diffuser are harmful effects of the fluid flow. Therefore, the temperature distribution in the fluid and surface of the liner and diffuser, the form of swirls, turbulence and velocity vectors have been investigatedby extracting the graphs of temperature, pressure and speed in different areas, so that the results can be used for optimization purposes of these systems in the future studies.

Key words: Exhaust diffuser, turbo machinery, liner, turbulence flow, optimization

INTRODUCTION

Gas turbines are now of top priority in the industry and has many applications in various industries including mechanics, aircraft engines and thermal powerhouses. Hence, the importance of research on gas turbines is clear. One of the most important parameters in gas turbines is the turbine efficiency and proper utilization of it. One of the sectors of turbine drawn the attention of researchers is gas turbine exhaust diffuser. Gas turbine exhaust diffuser includes an outer solid annular shell in which the liner is located radially protecting the outer part of the diffuser. Flow and temperature fields in this area cause deconstruction in the liners and diffuser. In the researches associated with this study we will see how speed and pressure fields affect the structure of the diffuser affect and deconstruct it. Diffuser efficiency depends on various factors such as the ratio of output to input area, angle ofcurrent expansion and length of the current path. An application of diffuser is their use in the wind tunnel, between the compressor and combustion chamber, between tow gas turbines and downstream of the turbine.

Most of gas turbine exhaust diffusers have geometric characteristic called liner connecting the inner wall to the outer wall. The task of these liners includes loadbearing base, cooling air path, oil path for bearings and other equipment and also exhaling hot air. In the diffusers with large angle, these liners cause a weak and turbulence in the flow route. One of the factors in the destruction of the gas turbine exhaust system liner and diffusers are temperature, high speed and pressure passing on them.

The purpose of this study is the numerical simulation of fluid flow and heat transfer of the gas turbine exhaust and also metal parts of the liner and diffuser. For this purpose, the effective parameters were extracted and the effect of different factors such as exhaust gas temperature, pressure and operating conditions on temperature distribution in the fluid and surface of the liner and diffuser, form of swirls, velocity vectors and the resulting turbulent flow will be discussed.

Some previous works: Ubertini and Desideri (2000) studied a small-scale laboratory model of gas turbinediffuser S.P.A. The model studiedforthe function of the geometry and the Reynolds number designed similar to GT diffuser and 24 fins were installedat the entrance to providefavorable input conditions in the industrial gas turbines diffuser. Dimensions of this model relative to the realgas turbine PGT10 model is equal to 0.35. To adapt the flow to the real model, Reynolds number was about 10^6 that is in accordance with the PGT10 gas turbine. In order to maintain the geometric similarity, the ratio of area and the ratio of length to diameter are considered to be 1.53 and 2.01 for modeling.

Peterasic Seume (2005) carried out a research on a scale model of gas turbine exhaust diffuser in which the ring studied was radial and used a variable rotation producer for the exhaust gas flow in accordance with different functions of gas turbines. The results of their work indicates that the diffuser without holder has a pressure more than the diffuser with the holder in all

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angles of rotation and recovery. Based on the test results, diffuser with cylindrical holder has higher recovery pressure than the diffuser with silhouette holder at all angles of rotation.

Kim *et al*. (2011) performed an analysis on heat transfer and forecasted the lifetime of the outer part of the shell and the liner of gas turbine combustion chamber with internal coolant flow. The method used in their study was a process in the design of cooling systems to improve the lifetime of materials for enhancing the cooling efficiency. Based on the results, a lot of thermal changes occur from the beginning to the end of work between the hot and cold surfaces in the areas welded close to the cooling hole and upstream of the C-channel divider. These three areas are in a very poor thermal cycle and it would correspond with cracked areas in actual gas turbine chambers.

Djebedjian and Renaudeaux (1998) performed a numerical analysis on the separated and turbulent flow in steam turbine engine exhaust diffuser with 22 cylindrical bases. In this study, numerical modeling was carried out for the diffuser and the results were compared with experimental results for the coefficient of static pressure.

Su and Zhu (2000) carried out a numerical study on the interaction of the combustion chamber and diffuser using the KIVA-3V code; their results suggest that the inputnon-uniform rate affects the temperature distribution.

Mustafa *et al*. (2006) tested an annular channel of a specific part of transfer of gas turbine engine. Their research indicates a gradual increase in pressure along the channel axis which prevents the separation of flow and the formation of secondary flow in the channel. Axial component of stress also causes a density and the amount of it was almost uniformly along the axis.

Martin *et al*. (2009) reexamined the gas turbine exhaust system used in marine industries and numerically analyzed the flow inside the system. Based on the results, changes have been made in the main design of the exhaust gas system to reduce stresses and failures.

Bheemaraddi and Kumarappa (2014) numerically investigated the turbulent boundary layer for a diffuser after gas turbine combustion chamber. In this study, SST k-ω method was used forturbulence flow modeling and the pressure drop for different arrangements of diffuser's fins with diffuser without fins were compared.

Chattan *et al*. (2013) numerically examined PGT10 gas turbine exhaust diffuser and considered the effects of fins and their number. They concluded that an increase indivergence factor of diffuser to 11° will increase the static pressure and recovery pressure factor. With further increasing divergence factor of diffuser, the pressure recovery factor decreases which reduces the efficiency of the turbine.

Gas turbine: The first gas turbine was built in 1791 by John Barber. The first real test of gas turbine operation was performed by Stolz in 1900 that had very low efficiency. Gas turbine produces power by applying the energy of fuel gases and air with high pressure and temperature with expanding it in several levels of fixed and moving fins. Axial compressors are used with several levels for high production of combustion chamber (around 4-13 atmospheres) of. The air pressure intakeby the compressor is increased at teach class. The compress or circulates by turbine, so theaxis of compressor and turbine is connected. If we assume that everything is ideal, meaning that friction and thermodynamic losses of fluid are zero then all processes at all levels of compressor and turbine are ideal and the pressure drop in the combustion chamber is also zero. If we left the entire system after commissioning of gas turbine (without fuel consumption), the power generated by the turbine should be equal to the power consumed by the compressor. But, it is scientifically impossible because most of the power generated in the gas turbineused to rotate the compressor and what remains is used to produce electricity (or whatever else) as output work. Therefore, the power produced by the turbine must be greater than the power consumed by the compressor; for this purpose, we can enhance the volume of fluid in constant pressure or increase its pressure in constant volume to increase the power produced by turbine. A combustion chamber is needed to raise the temperature of the working fluid so that the temperature rises by fuel combustion. In this way, a simple-cycle of gas turbine includes parts of the compressor, heating room and turbine (Razak, 2007). One of two types of diesel fuel or natural gas may be usedin the gas turbines. All parts of the gas turbine are placed in a chamber called engine casethat the beginning and end of this case is tube-shaped and placed horizontally.

The first purpose of using this diffuser in gas turbines is to achieve increased pressure that's why it is widely used in industries. Gas turbine exhaust diffuser recovers static pressure by reducing theflow rate which increases the compression ratio, output work and efficiency of the turbine. In other words, it can be said that exhaust diffuser is an important member in turbo machinery to achieve better efficiency.

Most of gas turbine exhaust diffusers have geometric characteristiccalledliner connecting the inner wall to the outer wall. The task of these liners includes load bearing base, cooling air path, oil path for bearings and other equipment and also exhaling hot air. In the diffusers with large angle, these liners cause a weak and turbulence in the flow route. V94.2 gas turbine exhaust system chamber has six liners in output. One of the factors in the destruction of the gas turbine exhaust system liner and diffusers are temperature, high speed and pressure passing on them. Reduced working life and the creation and growth of cracks in the liner and diffuser are damaging effects of fluid flow. In this regard, one of the problems that arise in almost all gas turbines is crack in exhaust turbine diffuser and liner. By the creation of the cracks in the diffuser and liner, the possibility of separation of liners or exit of hot gases, creation of considerable heat loss from the exhaust and reduced power and efficiency of gas turbines and as well as damaging other equipment will be there. In order to optimize the use of gas turbines, in this study, the numerical simulation of fluid flow and heat transfer of exhaust gas from turbine and also the metal parts of liner and diffuser and the factors affecting the destruction are studied.

MATERIALS AND METHODS

Modeling and numerical simulation: We have to use a mathematical model to describe the problem and the simulation should be used to show the results. According to information available from basic profile of the piece and assuming the other diffuser's parameters, the design was done by the Solid Works Software. Information available to the design of the diffuser are shown in Table 1.

For better investigation of the diffuser information, the pictures of it are presented in Fig. 1. As you can see in these pictures, in addition to the fins, the liners and place of repaired welds can be observed. One of the materials that make a difference in the results from software analysis and real technical information is the lack of attention to these restoration works on the inner surface of the diffuser. Because, the roughness on the surfaces increases the friction between fluid and inner surfaces and causes a drop in the fluid flow through the diffuser.

According to the information available from the diffuser as well as assuming other parameters, the geometry of diffuser was built in Solid Works Software. A 3D view of the diffuser is shown in Fig. 2.

There are six Liners in this diffuser with 60° to each other. As the length of fins is 106 cm, the diameter of the inner wall is considered to be 118 cm. Also, according to the figures of the diffuser, the length of the inner wall is 2 m. Front view and side view of the diffuser is modeled and the dimensions are shown in Fig. 3. In this model, the

Table 1: Information available to the design of the diffuser

Diffuser	Temp.
Diffuser in let temperature	532°C
Liner diameter (diffuserinlet)	330°C
Liner diameter (diffuser outlet)	360 cm
Diffuser length	420 cm
Fins length	106 cm
Fins thickness	10 cm

Table 2: The coefficients used in k-ω model

C_μ	$C_{\varepsilon 1}$	$C_{\varepsilon 2}$	K	ε
0.09	1.44	1.92	0.419	9.0

Fig. 1: A view from inside of the diffuser examined and location of the temperature sensor and repaired welds

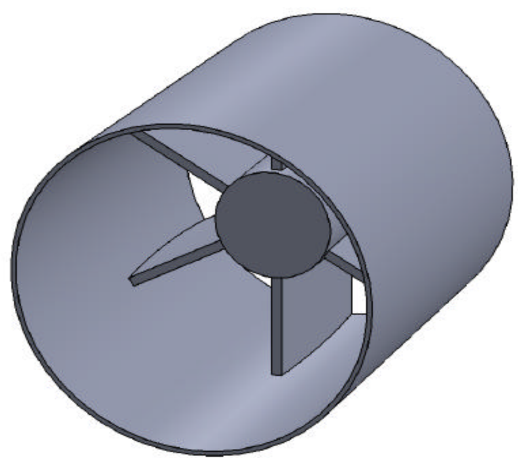

Fig. 2: The diffuser designed in Solid Works

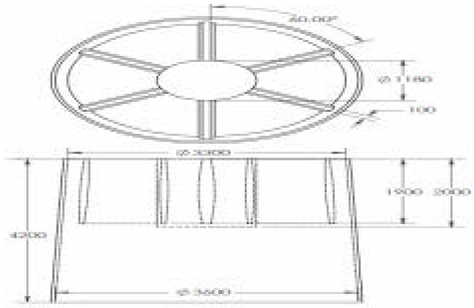

Fig. 3: Front view and side view of the diffuser modeled

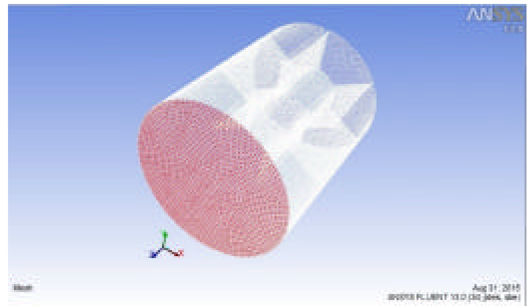

Fig. 4: A view of the meshed model

external wall thickness is considered 5 cm. The dimensions shown in Fig. 3 are in millimeters.

Governing equations: Chi-Epsilon turbulence model is one of the common turbulence models, although it has not good performance in large reverse pressure gradients. Chi Epsilon model is a 2-equation model, i.e., includes two additional transition equations for calculating the properties of flow turbulence. These equations can be used to calculate the effects of displacement and disruption on turbulence energy. The first transition variable is turbulence kinetic energy or Chi and the second transition variable in the model is turbulence lossor Epsilon. In other words, it can be said that Chi determines energy and epsilon determines turbulence scale. The main objective of Chi Epsilon model is improving Mixing-Length Model so that it could explain analgebraic expression for the length scale of turbulence in the flows with high complexity. Chi Epsilon model hasgood accuracy andperformancefor internal and external flows and the flows with limited wall with a relatively small pressure gradient. Consequently, the accuracy of the model decreasesforthe flows at high reverse pressure.

In the model examined in this study, Chi Epsilon Model is used for correct simulation of a turbulent flow and achieving accurate responses (Table 2).

Boundary conditions: According to available practical information about diffuser and relatively uniform conditions of its work, the boundary conditions considered for analysis in both cases are stable and unchanged. For boundary conditions input, the input mass conditions (10 and 100 kgs $^{-1}$) were used and fluid input temperature was 532°C (805 K) according to the available information from the diffuser. At the diffuser outlet, the pressure of exhaust products is equal to atmospheric pressure and the recurrent flow temperature was considered equal to ambient temperature. In the momentum equation, non-slip condition is assumed for diffuser walls. The diffuser's inner wall is Adiabatic and thermal boundary conditions is assumed for the outer wall. Ambient temperature is 300 K and the coefficient of heat transfer with the surroundings is 5 w m^{-2K-1}. Heat transfer in the liners is assumed equal to heat transfer from the liner base with the environment.

Ideal gas conditions have been used to calculate the fluid properties. To calculate the heat transfer from outer wall and calculating the external temperature, it is assumed that the wall is insulated with a thickness of 20 cm. Insulator properties are shown in the Table 3.

Table 3: Insulator properties for external walls

Density kg m^{-3}	Thermal capacity (j/kg K)	Thermal conductivity (w mK^{-1})
2320	1138	5/0

Table 4: The average exhaust temperature of the diffuser for three different computational network

Mesh number	Exhaust temperature average
780342	4/801
392557	5/801
205495	8/801

Computation network: Diffuser has been meshed by software Gambit. One of the requirements for numerical solutions is studying the sensitivity of software to the network. Little number of nodes increases the error of discretization. It is obvious that an excessive increase of nodes will result in persistent error and this error came from rounding the numbers by computer. However, there is a number of nodes in which the errors are minimized. Three different Meshing has been used for mesh optimization. Diffuser exhaust temperature average is calculated for each of the three computational networks shown in the Table 4. From another perspective, increasing the number of mesh will make the process of problem solving difficult. In fact, the choice of optimal number of mesh requires an overview of the conditions of the fluid in the diffuser and the critical areas at different levels in order tolook more closely at the behavior of fluids in critical areas and achieve accurate responses by centralizing the meshes. Figure 4 shows a view of the meshed model. As visible, the messes around the liners and where they are concentratedtodiffuser wall are more concentrated (Table 4).

As it turns out, the average exhaust temperature for three computational networks are close to each other with very high accuracy. Given that the accuracy of continuity equation solution in a network with 205495 meshes doesn't reach to the specified criteria (1×10^{-4}), a network with 392557 meshes is used. It is noteworthy that the convergence criterionis 1×10^{-5} for the momentum equation and is $1\times10^{-6}$for energy equation.

RESULTS AND DISCUSSION

The results of the pressure field: One of the main objectives of using diffuser at the bottom end of the turbine is to reduce the pressure at the end of the turbine and increase the turbine pressure ratio that enhance the efficiency of the gas cycle. In Fig. 5, pressure counter is shown in the middle section of the diffuser. As it can be seen, due to the swirls occur behind the inner wall of the diffuser, a drop is created in the direction of fluid flow and the pressure decreased locally but generally the pressure increases along with diffuser. An inner wall causes a disturbance in the pressure field and reduces the efficiency of the diffuserby creating swirls and localized pressure drop. The pressure increase is 164 kPa.

The comparison between the pressure contour in two Debi showed that an increase in the mass Debi of the fluid passing the diffuser had little impact on output results and create a little difference in the counters.

The results of the velocity field: Input mass Debi has been used for the boundary condition entering the diffuser. In the first case, the mass Debi was 10 kg s^{-1} and in the second case it was 100 kg s^{-1}. Given the boundary conditions intended to inlet section (L = 0 m), the velocity profile is uniform (about 3.8 m sec^{-1} for the first case and 38 meters per second for the second case).

The results of the temperature field: Internal and external wall temperature is very effective for the analysis of diffuser structures can be said that thermal stresses are dominant force in the structural analysis of diffuser.

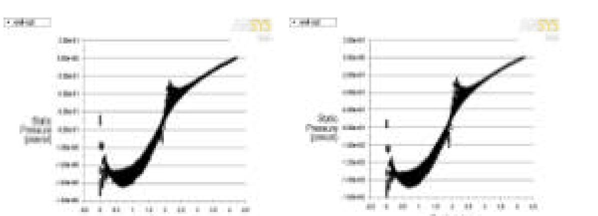

Fig. 5: Changes of pressure in the external wall of diffuser along with the diffuser's length for Debi q = 10 kg $^{s-1}$ and q = 100 kg^{s-1}, respectively, from left to right

Diffuser's inner surface temperature depends on the type of insulation used. Insulating properties are shown in the Table 4. In this analysis, insulation thickness is 20 cm. According to the results, the temperature of the inlet edges is some what equal to the temperature of input fluid that is reduced during the diffuser due to the heat transfer with the walls. The wall temperature is dependent on the fluid Debi. As Debi increases, due to the increased speed, fluid has less time for heat transfer with the wall, so the temperature reduction in this case is lower.

CONCLUSION

One of the most important parameters in gas turbines is the turbine efficiency and proper utilization of it. One of the sectors of turbine drawn the attention of researchers is gas turbine exhaust diffuser. First, a general introduction to the subject was proposed to determine the motives of this study and then some applications of this research were mentioned and the importance of and the reasons for doing this research have been investigated.

One of the factors in the destruction of the gas turbine exhaust system liner and diffusers are temperature, high speed and pressure passing on them. Reduced working life and the creation and growth of cracks in the liner and diffuser are damaging effects of fluid flow. So, in this study we model the flow and heat transfer and therefore the temperature, high pressure and velocity of flow passing on the exhaust system liners and diffusers.

In this study, considering the images of diffuser and the data from its structures, the geometry of diffuser was modeled in Solid Works Software. The geometry modeled to create the computational grid and meshing was transferred to Gambit Software. According to the terms of the problems and studying the mesh produced at the end, a model with 392557 meshes was selected as optimal computational grid optimization. The mesh generated for analysis offlow and heat transfer was transferred to ANSYS FLUENT. The flow and heat transfer equations were examined in this software in three-dimensional steady state.

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