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Research Paper

Effect of internal heat leakage on the performance of a high pressure ratio centrifugal compressor

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HIGHLIGHTS

- The effects of internal heat leakage intensifies with increasing the pressure ratio.
- Internal heat leakage should be considered at the pressure ratio higher than 5.
- Internal heat leakage inside the impeller reduces the impeller maximum temperature.
- Heat leakage inside the casing degrades the compressor performance.

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ABSTRACT

Centrifugal compressors are widely used in compact gas turbines in industrial and military applications where a high pressure ratio in small size is needed. The trend in centrifugal compressor is high pressure ratios and high efficiencies. However, higher pressure ratio increases the temperature difference between upstream flow and downstream flow which leads to a heat leakage from downstream to upstream through the solid parts. This heat leakage negatively affects the performance as well as the reliability of the compressor. In this study the effect of heat leakage through solid impeller and casing on the compressor performance has been studied for different pressure ratios. The compressor performance has been calculated using a three dimensional numerical model. Conjugate Heat Transfer (CHT) method has been used to calculate the temperature in the solid parts. The results show that the internal heat leakage through both the impeller and casing reduces the efficiency by 2.5% and the total pressure ratio by about 0.83 at pressure ratio up to 11. The effect of the internal heat transfer on the compressor performance is more noticeable at pressure ratios higher than 5. Meanwhile, heat transfer inside the solid impeller alone from the hot region to the cool region reduces the maximum impeller temperature while this heat leakage has a small effect on the compressor performance. However, heat leakage inside the casing alone slightly increases the impeller temperature while it strongly affects the compressor performance.

1. Introduction

Demands for compact, efficient high pressure ratio centrifugal compressors are increasing in both commercial and military applications. Such compressors reduce the size and weight of the system. However, high rotational speed of the impeller and high Mach number of flow require a carefully designed compressor to maintain the reliability and efficiency. The main focus of recent studies about centrifugal compressors with high pressure ratio was to increase the efficiency [1–4].

Another factor that affects the compressor efficiency is the heat transfer. Usually the compressor is not adiabatic, and therefore there is heat exchange between the compressor and the surrounding. For instance, for a turbocharger installed in a car, the heat transfer from the engine and the turbine to the compressor is proved to reduce the efficiency of the compressor by about 25% on average [5]. Meanwhile, heat transfer to the compressor increases the impeller temperature which degrades its reliability. The maximum pressure ratio in which the impeller can bear will be reduced if the effect of heat transfer to the solid impeller is taken into account because the allowable ultimate stress is reduced with increased temperature [6].

Heat transfer to the outside or cooling on the other hand improves the performance and reliability of the compressor.

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Nomenclature

h	specific enthalpy (J/kg)
D_2	impeller diameter (mm)
F_2	blending function (–)
f_r	correction factor (–)
m	mass flow rate (kg/s)
n	rotational speed (rpm)
P	pressure (Pa)
P_k	shear production of turbulence (kg/m s^3)
P′	corrected pressure (=p + 2ρk/3)
q	heat transfer per mass flow (J/kg)
R	specific gas constant (J/kg-K)
Re	Reynolds number (ρUL/μ)
s	entropy (J/kg K)
S_m	momentum source term
S_E	energy source term
T	temperature (K)
Z	number of blades or vanes (–)
U	velocity (m/s)
u	velocity fluctuation (m/s)
y+	dimensionless wall distance (–)

Greek symbols

∇	nabla sign
μ	air viscosity (kg/m s)
λ	thermal conductivity (W/m K)
η	efficiency (%)
ρ	density (kg/m^3)
τ	shear stress (N/m^2)

Subscriptions

p	polytropic
s	isentropic
t	turbulence
0	stagnation condition
1	inlet
2	outlet
θ	tangential direction

Gwehenberger [7] found that cooling a centrifugal compressor allows the compressor pressure ratio to increase from 5.2 to 5.8. Also cooling itself can increase the pressure ratio and efficiency of the compressor by changing the thermodynamical path of the compression process [8].

There is a temperature increase in compressors resulted by compression of the flow. The resulted temperature difference produces a heat flux in the solid parts from high temperature regions located in downstream to low temperature regions in upstream. This heat leakage is more noticeable in centrifugal compressors due to small distance between downstream and upstream. The heat leakage through the solid parts affects the efficiency as well as the reliability of the compressor. Gu [9] studied the effect of internal heat transfer as well as heat transfer to a centrifugal compressor through different parts. They reported that for a centrifugal compressor with pressure ratio of 2.8, internal heat leakage reduces the compressor efficiency by 0.85%. Their study focused on the design point and they also neglect the heat transfer in the casing in the backplate.

Based on the results obtained by Cui [10], internal heat transfer affects the compressor efficiency considerably and the amount of heat circulating through the solid parts of compressor ranges from 5% to 9% of the input energy of the impeller. This high circulation of heat transfer can have a huge effect on the flow field and performance of the compressor as well as temperature of different parts. This heat transfer is usually neglected in compressor CFD calculations, which may lead to significant errors in the results.

In this paper the effects of internal heat leakage on the performance and reliability of a high pressure ratio centrifugal compressor have been studied using a three dimensional RANS model. The heat leakage originated in the compressor casing or the solid impeller, from hot downstream to the cool upstream. The heat leakage through both routes together and only one route was studied in different pressure ratios.

2. Numerical model

2.1. Compressor geometry

The compressor has an impeller with 9 blades and 9 splitters. The compressor parameters are shown in Table 1. Only one passage including one main blade and one splitter is modeled for calculation. Solid casing was designed according to conventional designs of high pressure ratio compressors in gas turbines (Fig. 1). The solid parts are made by aluminum with thermal con-

Table 1
Compressor parameters.

Parameters	Value and units
n, (Rotational speed)	100,000 (rpm)
m, (Mass flow rate)	0.71 (kg/s)
Z, (Blades number)	9 + 9 (–)
D_2, (Impeller outlet diameter)	120 (mm)
Tip clearance	0.5 (mm)
Air gap width	1 (mm)
Blade inlet angle	60 (°)
Back sweep	40 (°)
Re tip	4.96e6

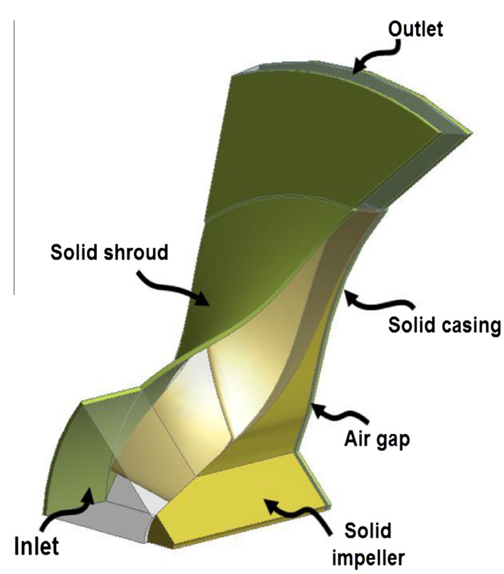

Fig. 1. One compressor sector and the solid parts.