INTERNATIONAL JOURNAL OF REFRIGERATION 60 (2015) 142–154

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Design optimization of a centrifugal compressor vaneless diffuser

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ARTICLE INFO

Article history:
Received 14 January 2015
Received in revised form 26 June 2015
Accepted 27 June 2015
Available online 14 August 2015

Keywords:
Compressor
Vaneless diffuser
Aerodynamic
CFD
Optimization
Available work loss
RSM
Thermodynamic optimization

ABSTRACT

Centrifugal compressors are used in many heat pumps and refrigeration systems. Radial vaneless diffuser is a principal component in these compressors. Therefore, the present research aims at improving the centrifugal compressor performance by optimizing the design of the radial vaneless diffuser. Two radial vaneless diffuser geometries were proposed, investigated and numerically optimized. The optimization aimed at minimizing the diffuser loss coefficient and maximizing the pressure coefficient. Simulations were performed by solving the Reynolds averaged Navier–Stokes equation under 2D axisymmetric condition. A genetic optimization algorithm was implemented in order to conclude the optimum diffuser geometry. 2D axisymmetric simulations with air and R134a as working fluids showed that the optimized geometry reduced the diffuser loss coefficient by up to 10% and increased the pressure coefficient by up to 3.8%. Additional 3D simulations with an impeller located before the diffuser were performed. These 3D simulations showed that the optimized diffuser geometry reduced the diffuser loss coefficient by up to 4.7% and increased the pressure coefficient by up to 6.6% under jet-wake and swirl flow conditions.

Optimisation de la conception du diffuseur sans aube d'un compresseur centrifuge

Mots clés : Compresseur ; Diffuseur sans aube ; Aérodynamique ; CFD ; Optimisation ; Perte de travail disponible ; RSM ; Optimisation thermodynamique

1. Introduction

Radial vaneless diffusers are found in fluid machines like refrigeration and industrial centrifugal compressors, automotive turbochargers' compressors, centrifugal circulators, and centrifugal pumps. They recover the fluid kinetic energy and hence increase its static pressure and density. Fluid diffusion significantly increases in radial diffusers with decreasing the flow rate and could eventually result in compressor surge. Shaaban (2004)

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http://dx.doi.org/10.1016/j.ijrefrig.2015.06.020

Nomenclature

AR	area ratio [–]
B*	normalized throat width [–]
b	diffuser width [m]
$C_{p,D}$	diffuser pressure coefficient [–]
D	diameter [m]
K_D	diffuser loss coefficient [–]
Mu	peripheral Mach number [–]
p	static pressure [Pa]
PG	pressure gradient [Pa m^{-1}]
PG*	normalized pressure gradient [–]
p_t	total pressure [Pa]
R*	normalized throat radius [–]
r	radius [m]
R_g	gas constant [J $(kg.K)^{-1}$]
Re	Reynolds number [–]
T	temperature [K]
u	local velocity [m s^{-1}]
V	mean velocity [m s^{-1}]
v_r	radial velocity [m s^{-1}]

Greek

κ	specific heat ratio [–]
μ	viscosity [Pa.s]
θ	diffuser angle [°]
ρ	density [kg m^{-3}]
ω	rotational speed [rad s^{-1}]

Subscript

1	diffuser inlet
2	diffuser outlet
i	domain inlet
max	maximum
MRD	modified radial diffuser
SRD	standard radial diffuser
t	throat

found that surge occurred in a small turbocharger compressor in conjunction with flow separation at vaneless diffuser inlet. He showed that the aerodynamic losses of a small turbocharger's vaneless radial diffuser represented 33–45% of the overall compressor aerodynamic losses at surge. Therefore, optimizing the design of vaneless radial diffusers could significantly improve the aerodynamic performance and stability of centrifugal compressors.

Many attempts have been made to optimize the design of radial vaneless diffusers. Brown and Bradshaw (1947) introduced a method to design radial vaneless diffusers using data given for simple conical diffusers. They reported that noticeable improvement in diffuser performance was obtained at high loads and tip speeds using this design method. Stanitz (1952) and Traupel (1977) presented simplified differential equations for the analysis of the flow in vaneless diffusers. Japikse (1984) discussed the design of vaneless diffusers. He reported that virtually every vaneless diffuser study has considered parallel walls. Whitfield and Baines (1990) and Aungier (2000) presented simple 1D methods for the design of vaneless diffusers. These methods usually contain empirical loss correlations which are not valid under all geometrical and operating conditions. Balje (1981) introduced an equation for the estimation of vaneless diffuser aerodynamic losses. Mohtar et al. (2011) experimentally investigated the performance of pinched and grooved vaneless diffusers. They showed that a pinched diffuser shifted the surge line to lower flow rates. Im (2012), Kus and Nekså (2013), Wang et al. (2013) and Schiffmann and Favrat (2010) developed design tools based on 1D loss correlations to design vaneless diffusers. Such simple design tools can only be used to obtain an initial diffuser design. This is because they are unable to catch the details of the complex diffusing flow within the diffuser under different geometrical and operating conditions. Adachi et al. (1992) experimentally investigated and optimized the effect of a tapered passage at the outlet part of a parallel walled vaneless diffuser. They showed that tapering the parallel walled diffuser by an optimum throttle ratio of 0.5 at the outlet part improved both the surge margin and the compressor efficiency over a wide range of flow rates. Jaatinen et al. (2011, 2013) experimentally investigated the effect of diffuser width on the performance of centrifugal compressor. They showed that pinch implemented in the shroud is more beneficial than pinch divided between the hub and the shroud of the compressor.

Many authors have used CFD codes for the analysis of the flow in vaneless diffusers. Tatar et al. (2008) implemented the standard k–ε model for the analysis of the flow in vaneless diffusers with straight walls and constant cross sectional area. They showed that the flow at diffuser inlet is highly non-uniform due to impeller jet-wake flow pattern. Moreover, blade wake mixed out very much quicker than passage wake because of the higher Reynolds stress levels. Jaatinen (2009) experimentally and numerically investigated the performance of five different vaneless diffusers using Chien's k–ε turbulence model. He also modeled some cases using the k–ω–SST turbulence model. Jaatinen (2009) showed that the k–ω–SST turbulence model predicted the flow fields better. Ljevar et al. (2005, 2006) numerically studied the rotating stall phenomena in wide vaneless diffusers using an incompressible viscous flow solver of the commercial software package Fluent. They found that the stability limit and the structure of a two dimensional rotating instability were influenced by the configuration geometry as well as the inlet and outlet flow conditions. Chuang et al. (2008) presented a two-dimensional mathematical model to investigate the effect of geometry on the instability of jet-wake in a vaneless diffuser. Their computational results showed that diffusers with large width to radius ratios have a different flow mechanism. Sheng et al. (2012) presented a 3D compressible flow model to study the occurrence of weak rotating waves in unparalleled wall vaneless diffusers of centrifugal compressors. They showed that contracting walls suppressed the rotating stall and the suppression effects were dependent on wall contraction rate, wall shape, inlet Mach number and the diffuser radius ratio. Colaciti et al. (2007) presented numerical simulation of turbulent flow through radial diffuser using the Reynolds stress, the k–ε, the RNG k–ε, and the k–ω–SST turbulence models. They compared their computational results to experimental data and showed the significance of the choice of the turbulence model on the physical quality and accuracy of numerical results. Deschamps