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Aerodynamic analysis of conical diffusers operating with air and supercritical carbon dioxide

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ABSTRACT

The design of efficient supercritical carbon dioxide (S-CO_2) turbomachinery to be used for power generation (and also for CO_2 capture facilities) has gained interest in recent years due to the compactness and good performance of the S-CO_2 recuperative Brayton cycle in nuclear, waste heat and solar applications. Presently, in addition to a large amount of theoretical work focused on the analysis and optimisation of the system, there are even some prototypes of centrifugal compressors running on experimental facilities like, for instance, the pilot plant at SANDIA National Laboratories engineered by Barber Nichols Inc. Nevertheless, the performance of this experimental unit is far from an equivalent air/gas turbomachinery, say 80% compressor efficiency, mainly due to a lack of knowledge about the particular behaviour of this working fluid. The need to research these aspects of turbomachinery design has already been identified by the scientific and industrial communities.

This work aims to provide more information about diffusion of S-CO_2 flows in conical ducts based on the experimental work on air diffusers carried out from the sixties to the eighties (in particular the test conducted by Dolan and Runstadler in 1973). Following a similar approach but by means of numerical analysis (CFD) rather than tests, the work presented here provides a comparison of the expected performance when S-CO_2 is used. It is observed that this new working fluid is likely to enhance the pressure rise capability while, at the same time, contribute to reducing the total pressure losses with respect to air.

The work commences with a brief introduction to the fundamentals of conical diffusers followed by a discussion on the methodology, mesh size and convergence criteria. Then the most relevant geometric and aerodynamic parameters are assessed prior to providing some conclusions about the expected impact of using S-CO_2 on a radial compressor.

1. Introduction

The vital role played by diffusers to enhance the performance of turbomachinery has been traditionally acknowledged by aerodynamicists and other technicians working with hydro or gas turbines and with compression equipment (Dolan and Runstadler, 1973; Wilson, 1984; Japikse and Baines, 1998 and Henry et al., 1958). Whether it be for reducing the back pressure of a turbine or increasing the static pressure delivered by a compressor, diffusion is always present and has to be carefully analysed.

Diffusion is usually regarded as the capacity to convert dynamic head (kinetic energy) into static pressure (enthalpy) by reducing flow velocity. How far this conversion proceeds is generally based on elementary aspect ratios of variable area ducts (diffusers or blade passages). Moreover, diffusion also takes place locally even if no changes are observed in the cross sectional area of the flow passage; e.g. bend in a constant-area duct or flow past an isolated aerofoil.

Diffusion processes lead to inevitable thickening of the boundary layer, with subsequent energy losses that are somewhat proportional to the fraction of kinetic energy converted into enthalpy. Thus, there is a need to fully understand the impact of all the parameters involved (geometric and aerodynamic) in order to optimise the performance of diffusers (highest pressure recovery with lowest energy loss). Regrettably, no such analysis is available to date, as highlighted by Wilson (1984), and many industrial practises still rely on the experimental work developed by Dolan, Runstadler and other researchers some forty years ago (Dolan and Runstadler, 1973 and Henry et al., 1958). These authors acknowledged the need to provide designers with some sort of performance maps that would make it possible to develop highly efficient compression devices.

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Nomenclature

Latins	
A	area (m^2)
AR	area ratio (–)
C_p	pressure rise coefficient (–)
D	diameter (m)
e_a	approximate relative errors (–)
F_S	safety factor (–)
GCI	grid convergence index (–)
h	enthalpy (kJ/kg)
K	total pressure loss coefficient (–)
L	length (m)
M	Mach number (–)
$\dot{m}$	mass flow rate (g/s)
N	number of cells (–)
o	order of accuracy (–)
p	static pressure (Pa)
q	parameter of grid convergence analysis (–)
T	temperature (K)
Re	Reynolds number (–)
r	refinement ratio (–)
S	surface (m^2)
s	entropy (kJ/kg K)
v	velocity (m/s)

Greeks	
δ^*	displacement boundary layer thickness (mm)
ε	absolute error, tolerance (–)
η	efficiency (–)
θ	half cone angle (°)
λ	mesh size (mm)
μ	dynamic viscosity (kg/m s)
ξ	flow variable of interest
ρ	density (kg/m^3)
τ_w	wall shear stress (Pa)

Subscripts	
1	diffuser inlet, coarser mesh
2	diffuser outlet, finer mesh
3	intermediate mesh
0	stagnation condition
a	actual
id	ideal condition
is	isentropic
t	theoretical
th	throat

The present work aims to provide basic information that can be used to design turbomachinery (in particular turbocompressors) operating with supercritical carbon dioxide. This is a necessity already evidenced by leading researchers who have claimed that the information currently available for turbomachinery operating on air or combustion products is not necessarily applicable to this particular working fluid (Ulizar and Pilidis, 1997 and Ulizar and Pilidis, 1998). For instance, Ulizar and Pilidis claim, with regard to the development of CO_2 turbines, that "*the development of an extensive theoretical and experimental knowledge database will be necessary to support the development of these designs*" and add that the "*improvement and validation of computational fluid dynamic codes will be necessary to handle suitable gas mixtures*" (Ulizar and Pilidis, 1997). These statements are in good agreement with the comments by researchers from the Massachusetts Institute of Technology: "*the design of supercritical CO_2 turbomachinery is challenging due to the limited available previous analyses and experience; lack of understanding of compressor characteristics near the critical point, where real fluid properties change substantially, adds considerable complexity for compressor design*" (Wang et al., 2004).

2. Defining diffuser performance

Diffusers convert the inlet kinetic energy of a fluid into enthalpy (internal energy plus flow work) at the outlet. In particular, diffusion of a compressible gas in an adiabatic variable-geometry duct usually manifests as a reduction in velocity accompanied by an upsurge in static pressure. Total temperature remains constant whereas a variable total pressure drop which is proportional to the irreversibility of the process takes place. Thus, the most commonly used parameter to characterise the performance of a diffuser is the pressure rise coefficient (C_p), defined as the ratio of static pressure rise to inlet dynamic head (kinetic energy):

$$C_p = \frac{p_2 - p_1}{p_{01} - p_1} \tag{1}$$

where 1 and 2 stand for the inlet and outlet sections of the diffuser respectively.

Nevertheless, the pressure rise coefficient does not suffice to characterise the performance of a diffuser since it accounts only for the fraction of dynamic head that is converted into enthalpy. Thus, no information is given as to whether the remaining inlet kinetic energy is lost or is still present in the outlet section. This is quantified with either the total pressure loss coefficient (K) or the diffuser effectiveness (η):

$$K = \frac{p_{01} - p_{02}}{p_{01} - p_1} \tag{2}$$

$$\eta = C_{p,a}/C_{p,t} \tag{3}$$

where the inlet and outlet total pressures (p_0) in Eq. (2) are mass-averaged magnitudes.

The effectiveness of a diffuser is defined as the ratio of actual pressure rise ($C_{p,a}$) to theoretical pressure rise ($C_{p,t}$) of an ideal diffuser with the same geometry and inlet conditions but no energy losses. If the flow is assumed incompressible, the application of Bernoulli's equation under constant total pressure conditions yields the following simplified expression of Eq. (3) (Wilson, 1984):

$$\eta = \frac{C_{p,a}}{1 - (v_2/v_1)^2} \tag{4}$$

which suggests that pressure rise is highest when outlet velocity is lowest, should efficiency be constant.

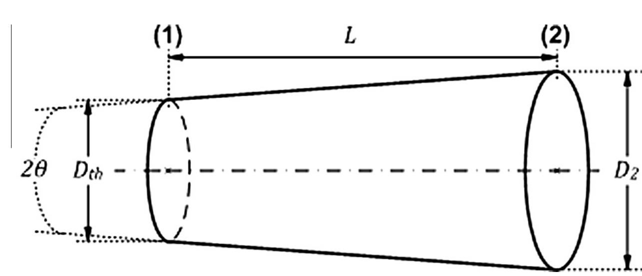

Fig. 1. Geometry of a standard conical diffuser.