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Numerical simulation of combined screw compressor–expander machines for use in high pressure refrigeration systems

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Abstract

Recent interest in natural refrigerants has created a new impetus for studies of CO_2 as a working fluid in vapour compression systems for refrigeration and air conditioning. Two major drawbacks to its use are the very high pressure differences required across the compressor and the large efficiency losses associated with the throttling process in the refrigeration cycle. It is shown how these disadvantages can be minimised by the use of a screw machine both to compress the gas and use the expansion process to recover power. Both these functions can be performed simultaneously, using only one pair of rotors, in a configuration that partially balances out the forces induced by the pressure difference and hence, reduces the bearing loads to an acceptable level. A further feature is the use of rotors, which seal on both contacting surfaces so that the same profile may be used for the expander and the compressor sections. This enables the rotors performing both these functions to be machined or ground in the same cutting operation and then separated by machining a parting slot in them. Computational Continuum Mechanics comprising both, fluid flow and structural analysis is used in this paper for the investigation of fluid-solid interaction in such machines.

Keywords: Screw compressor; Screw expander; Computational fluid dynamics; Mathematical modelling

1. Introduction

Nearly 20% of the electricity produced in developed countries is used to drive compressors, the majority of which are required for air-conditioning and refrigeration systems. There are therefore considerable environmental advantages to be gained by improving the efficiency of such systems and the compressors that drive them. A further requirement for environmental protection is the need to minimise the use of refrigerants, which may lead to the breakdown of the ozone layer in the upper atmosphere. As a result of the latter requirement, in the last few years there has been a growth of interest in the use of natural fluids as refrigerants, in place of the halogenated hydrocarbons now widely used. One of these natural refrigerants is CO_2, which is totally free from ozone breakdown effects. Despite the environmental advantages of CO_2 as a working fluid

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Nomenclature

C	constant in the turbulence model
$\mathbf{F}$ [N]	body force
$\mathbf{i}$	unit vector
$\mathbf{I}$	unit tensor
k [m^2/s^2]	kinetic energy of turbulence
m [kg]	mass
$\dot{m}$ [kg/s]	source in pressure correction equation
p [Pa]	pressure
P	production of turbulent kinetic energy
$\mathbf{q}$	source term
$\dot{Q}$ [J/s]	source in the energy equation
$\mathbf{s}$ [m^2]	control volume surface
t [s]	time
$\mathbf{u}$ [m]	displacement in solid
$\mathbf{v}$ [m/s]	fluid velocity
V [m^3]	volume
x [m]	spatial coordinate
z [m]	axial coordinate
Γ	diffusion coefficient
ε [W/kg]	dissipation of kinetic energy
ϕ	Variable in transport equation
λ	Lame coefficient
μ [m^2/s]	viscosity
η	Lame coefficient
ρ [kg/m^3]	density
σ	Prandtl number
Δt [s]	time step used in the calculation

Indices

add	added or subtracted
eff	effective
rec	receiver
T	turbulent

in vapour compression systems for refrigeration and air conditioning, there are two major drawbacks to its use. These are the very high pressure differences required across the compressor, which may be as high as 60 bar, and the large efficiency loss associated with throttling over such a large pressure drop in the near critical region.

The magnitude of this loss can be better appreciated by the analysis of a typical CO_2 system, as shown in Fig. 1. In this case, in an idealised reversible cycle, recovery of the throttle losses, by controlled expansion, will increase the COP by as much as 72%. In a practical system, this gain would be reduced by the compression and expansion efficiencies, which would reduce the expansion work and increase the compression work but even then, the potential benefits are so large that some form of power recovery from this expansion process is essential if the resultant coefficient of performance (COP) is to be acceptable.

To recover power from the throttle loss in an economic manner, a number of proposals have therefore been made to use various types of positive displacement machines, mainly of the vane type [4], in such a manner that compression in one part of them is combined with recovery of work from simultaneous expansion in