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Original article

The influence of timed coolant injection on compressor efficiency

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ABSTRACT

Timed injection of coolant during the onset of the compression stroke in a reciprocating compressor aimed at achieving quasi-isobaric conditions during the initial part of the compression stroke was investigated as a means of improving compressor efficiency. It is found that an isobaric cooling process followed by an isothermal compression process requires less energy than an isothermal compression process for the same boundary conditions. Achieving isobaric cooling in a real reciprocating compressor would require sudden and significant cooling during the onset of compression. A simplified process model of a real reciprocating compressor was created. It modelled the timed cooling process as a polytropic process with reduced polytropic index. An experimental compressor, equipped with a coolant injection system, was constructed. Dry baseline tests and tests with continuous and timed coolant injection were conducted. It was found that timed injection during the onset of compression, while also keeping the suction valve closed to prevent additional suction air inflow, yields an additional compression work-saving advantage over continuous coolant injection for the same set of boundary conditions. The simplified process model and numerical simulation were validated against the experimental results and were found to agree well with the experimental results.

Introduction

Compressors are widely used and are essential to many industries and applications. The electricity demand of compressed air systems constitutes approximately 10% of total industrial demand in many industrial countries [1]. Furthermore, the energy cost of industrial compressors constitutes more than approximately 76% of their total life-cycle cost [1,2]. As part of a broader initiative aimed at combating global heating and climate change, many countries and institutions understand the importance of efficiency improvement to reduce electricity demand and thus carbon dioxide emissions, which are emitted by fossil fuel burning power stations [3,4]. Consequently, research on the improvement of compressor efficiency is widely undertaken, because a saving in this area would mean large overall savings in electricity consumption. One focus area of efficiency improvement is to explore the possibility of reducing the heat of compression by employing coolant injection to affect quasi-isothermal compression. A literature survey indicated that research on the injection of oil, water or refrigerants into various types of positive displacement compressor is indeed undertaken by many researchers (*cf.* Table 1).

One area that has not yet received attention is the timed injection of coolant during the onset of the compression stroke in a reciprocating compressor aimed at achieving quasi-isobaric conditions during the initial part of the compression stroke. The potential of this effect was investigated by means of a theoretical and experimental study [5].

Coolant injection in positive displacement compressors

When a gas undergoes isothermal compression the least amount of work is required [6] and this is therefore the most desirable process when compressing a gas. It is the equivalent of a compressor having an infinite number of stages with perfect intercooling between each stage [7]. Attaining isothermal or quasi-isothermal compression by means of injecting a fluid into positive displacement compressors has been widely researched (*cf.* Table 1).

Oil injection

Mostly, the injected liquid into flooded twin-screw compressors is a lubricant where the main purpose is lubrication, sealing, cooling or discharge temperature control and silencing [7–9]. Oil is injected into the compressor typically through one hole where the gas and oil inlet temperatures coincide [10]. Flooded twin-

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Nomenclature

A	area (m^2)
c	damping coefficient (Ns/m)
C_D	discharge coefficient for orifice flow
C_f	valve force coefficient
D	diameter (m)
k	spring stiffness (N/m)
m	mass (kg)
$\dot{m}$	mass flow rate (kg/s)
n	polytropic index
n	number of samples (functional analysis)
P	pressure (Pa)
Q	heat transfer (J)
S/s	samples per second
t	time (s)
T	temperature (K)
$\mathtt{T}$	period (s)
u	specific internal energy (J/kg)
U	internal energy (J)
V	volume (m^3/kg)
v	velocity (m/s)
W	Work (J)
x	displacement, valve motion (m)

Greek letters

γ	ratio of specific heats C_p/C_v
η	efficiency (%)
θ	angle of rotation (rad)
ρ	density (kg/m^3)
ω	angular velocity (rad/s)

Subscripts

c	cylinder
$cool$	cooling or cooled
cle	clearance
d	discharge
dv	discharge valve
I	indicated
i	index variable
$isoth$	isothermal
o	initial
s	suction
str	stroke
sv	suction valve
v	valve

Table 1
Selection of published research on positive displacement compressor coolant injection.

Research group	Date	Reference	Type of cooling			Compressor type			
			Oil injection	Water injection	Refrigerant injection	Recipro-cating	Screw	Scroll	Rotary Vane
Qin and Loth	2014	[18]	x	x		x			
Valenti et al.	2013	[12]	x						x
Bell et al.	2012	[14–17]	x					x	
Xu et al.	2011	[19]			x	x	x	x	x
Georgiou and Xenos	2010	[20]		x					x
Kim and Favrat	2010	[21]		x				x	
Kremer et al.	2010	[22,23]	x			x			
Van de Ven and Li	2009	[24]		x		x			
Jianfeng et al.	2009	[25]					x		
Wang et al.	2009	[26]			x			x	
Hugenroth et al.	2007	[27]	x					x	
Yuanyang et al.	2006	[28]		x				x	
De Paepe et al.	2005	[29]	x				x		
Zhao et al.	2005	[30]		x				x	
Nichol	2003	[31]		x			x		
Malmgren et al.	2003	[32]		x		x			
Cho et al.	2003	[33]			x			x	
Coney et al.	2002	[34]		x		x			
Dutta et al.	2002	[35]			x			x	
Park	2002	[36]			x			x	
Winandy et al.	2002	[37]			x			x	
Schick and Knasiak	2000	[38]	x						
Heidrich	2000	[39]		x			x		
Sangfors	1998	[40]	x	x			x		
Martinez and Pallaver	1993	[41]	x				x		
Chiu and Zaloudek	1987	[42]							
Westphal	1978	[43]		x					

screw compressors are common in industry [10]. Single-screw compressors are also lubricant injected compressors [8, pp. 413-420] where the lubricant injection has the same aim as in the case of flooded twin-screw compressors.

Some rotary sliding vane compressors also make use of oil injection for the same reasons as described above [8,11]. Recently, Valenti et al. [12] reported that with sufficient oil droplet atomization, a 23–28% energy saving is possible in sliding vane compressors.

Bell et al. [13–16] conducted research on cooling and flooding a scroll compressor with the aim of energy efficiency improvement. They injected large quantities of oil into the working chamber in