Applied Thermal Engineering 111 (2017) 903–913

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

An investigation of heat transfer losses in reciprocating devices

Caroline Willich [a], Christos N. Markides [b], Alexander J. White [a,*]

[a] Department of Engineering, Cambridge University, CB2 1PZ, United Kingdom
[b] Department of Chemical Engineering, Imperial College, London SW7 2AZ, United Kingdom

HIGHLIGHTS

- Computed dissipation in gas springs matches experiment over a wide speed range.
- A gas spring with internal grid has been simulated to mimic valve flow.
- Grid-generated motions roughly double the thermal loss at high Peclet number.
- Thermal loss is significant in the context of high-efficiency compressors.

ARTICLE INFO

Article history:
Received 27 July 2016
Revised 20 September 2016
Accepted 24 September 2016
Available online 28 September 2016

Keywords:
Reciprocating compression
Reciprocating expansion
Irreversible heat transfer
Gas springs
Hysteresis loss

ABSTRACT

The paper presents a detailed computational-fluid-dynamic study of the thermodynamic losses associated with heat transfer in gas springs. This forms part of an on-going investigation into high-efficiency compression and expansion devices for energy conversion applications. Axisymmetric calculations for simple gas springs with different compression ratios and using different gases are first presented, covering Peclet numbers that range from near-isothermal to near-adiabatic conditions. These show good agreement with experimental data from the literature for pressure variations, wall heat fluxes and the so-called hysteresis loss. The integrity of the results is also supported by comparison with simplified models. In order to mimic the effect of the eddying motions generated by valve flows, non-axisymmetric computations have also been carried out for a gas spring with a grid (or perforated plate) of 30% open area located within the dead space. These show significantly increased hysteresis loss at high Peclet number which may be attributed to the enhanced heat transfer associated with grid-generated motions. Finally, the implications for compressor and expander performance are discussed.

1. Introduction

Reciprocating compressors and expanders have a wide range of potential applications for energy conversion systems. Examples include reciprocating Joule cycles for combined heat and power plant [1], heat pumps [2], Stirling engines (e.g., for solar applications [3]) and free-piston engines [4]. The present study was motivated by applications in energy storage, specifically the 'pumped heat energy storage' (PHES) system described in Refs. [5,6]. One advantage of reciprocating devices for such purposes is that, relative to turbomachinery, they offer the potential for high compression and expansion efficiency. This is especially true for low-power systems for which turbomachines suffer high leakage and windage loss. Furthermore, a single device may serve as both a compressor and expander by adjustment of valve timings. This is beneficial for energy storage applications as it reduces the cost and turn-round time between charge and discharge.

The potential for high efficiency of reciprocating devices is rooted in the near-reversible behaviour of gas systems when subjected to pure displacement work, at least in the isothermal and adiabatic limits. For real machines, several irreversible processes nonetheless occur, including throttling through valves, mixing of inlet and residual gas, and leakage past piston rings. Various mechanical losses also occur due to friction in bearings, valve gear and piston rings. Methods of mitigating against these are discussed in Refs. [1,5] and include reducing piston speed and maximising valve open areas. However, once these losses have been minimised the effects of heat transfer are likely to remain a major factor limiting efficiency. In this respect it is important to note that, even if the device is insulated such that processes are globally adiabatic, heat exchange to and from the cylinder walls (but with no *net* heat transfer) is inherently irreversible and incurs an exergetic loss. The main purpose of the present paper is to investigate this loss using

* Corresponding author.
E-mail address: ajw36@cam.ac.uk (A.J. White).

http://dx.doi.org/10.1016/j.applthermaleng.2016.09.136
1359-4311/

CFD analysis, the ultimate aim being to determine what impact it has on compression and expansion efficiency and what steps can be taken to reduce it.

1.1. Previous work

In the 1960s Annand [7] reviewed published experimental work on heat transfer in IC engines, concluding that the use of traditional heat transfer coefficients (HTCs) was not suitable because the heat flux and driving temperature difference are not in phase. A simple 1-D heat conduction analysis by Pfriem [8], using small amplitude pressure fluctuations to model work transfer, had however already established that unsteady effects could be modelled with a *complex* HTC. Later work by Lawton [9] replaced the pressure fluctuations with volume fluctuations, these being better defined and independent of the machine speed.

Much of the current understanding of heat transfer irreversibility in reciprocating devices stems from research on valveless gas springs. Examples include the analysis of 'hysteresis loss' by Lee [10] using an approach similar to that of Pfriem, and the detailed loss measurements conducted by Kornhauser and co-workers (e.g., [11]) which generally agree well with Lee's theory. More recently, Bailey et al. [12] undertook similar experiments but with clearance (rather than 'sliding') seals, concluding that Lee's analysis remained valid provided account is taken of the pumping loss. Other recent work includes the conjugate heat transfer analysis by Mathie et al. [13] which shows that finite conductivity of the cylinder wall is an important factor for some combinations of gas and wall properties.

Detailed computational studies include the axisymmetric calculations devised by Catto and Prata [14] and the commercial CFD simulations of Lekic and Kok [15], both applied to gas springs. The former showed excellent agreement with Lawton's model for instantaneous heat flux, but agreement with the complex HTC model was less good. Lekic and Kok obtained good agreement between predicted heat fluxes and those derived from p–V measurements, as described further in Section 4.4. They also showed the presence of secondary flows near top and bottom dead centre, highlighting that flow patterns are quite complex even in the case of simple gas springs – i.e., without valve flows.

The specific contributions of the present paper are to validate CFD analysis (particularly its ability to predict hysteresis loss in gas springs) over the full range of speed from near-isothermal to near-adiabatic, and then to provide a preliminary study into the effects of grid-generated motions in order to mimic valve flows. The role of the above-mentioned secondary flows is also considered. Simplified models for property variations are presented alongside the CFD results, partly to ensure integrity of the numerical methods, but also as an aid to physical interpretation and as a check on the assumptions involved in deducing heat fluxes from experimental p–V data. We begin with a description of the hysteresis loss in gas springs and how this can be interpreted as an efficiency decrement.

Notation

A	piston area, m^2
A_s	internal surface area, m^2
c_p	isobaric specific heat capacity, J kg^{-1} K^{-1}
D	piston diameter, m
D_h	hydraulic mean diameter, $4V/\bar{A}_s$, m
ℓ	connecting rod length, m
k	thermal conductivity of gas, W m^{-1} K^{-1}
M	mass of gas, kg
p	gas pressure, Pa
Pe	Peclet number, see Eq. (1)
$\dot{Q}$	heat transfer rate *into* gas, W
$\dot{q}_w$	wall-to-gas heat flux, W m^{-2}
R	gas constant, J kg^{-1} K^{-1}
r_c	crank throw, m
r_v	volumetric compression ratio ($= V_{max}/V_{min}$)
s	stroke length ($= 2r_c$), m
T_b	bulk (mass-averaged) gas temperature, K
T_w	wall temperature, K
V	gas volume, m^3
$\dot{W}$	rate of work done *by* the gas, W
x	axial location in cylinder m
X	instantaneous piston position m
α	thermal diffusivity ($= k/\rho c_p$) m^2 s^{-1}
γ	ratio of specific heats
ζ	dimensionless loss, see Eq. (2)
ψ	efficiency decrement, see Eq. (4)
θ	crank angle, °
ω	anglar velocity, rad s^{-1}

Other symbols are defined in the text close to where they are used.

2. Thermal hysteresis in gas springs

A gas spring comprises a fixed mass of gas enclosed within a valveless cylinder-piston arrangement, as shown in Fig. 1. Applications include shock absorbers, hydraulic accumulators and free-piston Stirling engines, but gas springs also provide useful facilities for studying heat transfer effects. As shown the piston is driven by a motor so as to provide periodic compression and expansion which, after an initial transient, reaches a steady cyclic state. Due to the large thermal inertia, the cylinder and piston walls maintain an approximately constant and uniform temperature T_w, whereas the gas temperature adapts during the transient phase such that its minimum and maximum values straddle T_w. Thus, near top dead centre (TDC), when the gas is at its hottest, heat transfer tends to be from the gas to the walls (i.e., negative heat transfer), whereas it is in the opposite sense near bottom dead centre (BDC). As noted above, heat exchange cannot be modelled accurately using a traditional HTC because interaction between heat and work exchange result in the heat flux being out of phase with the temperature difference $\Delta T = T_w - T_b$, where T_b is the mass-averaged (or 'bulk') gas temperature.

The impact of gas-wall heat exchange depends largely on the rapidity of the compression-expansion process relative to the rate of heat transfer. This is quantified dimensionlessly by the Peclet number, Pe, which is proportional to the ratio between the thermal diffusion time and the rotational period,

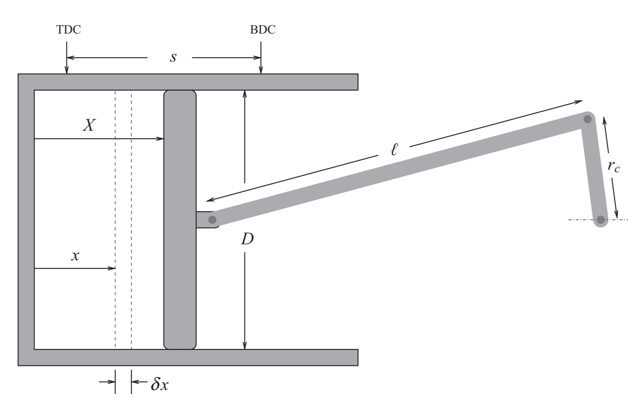

Fig. 1. Schematic of gas spring showing control volume (dashed line) used in the analysis of Section 4.2 and dimension definitions.