Numerical Modelling of the Gas Dynamics of a Prototype Free-Piston Engine

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keywords: free-piston, 1D gas dynamics, two-stroke, specific heat, chemical equilibrium, charging, scavenging, tuning

CERTIFICATE OF AUTHORSHIP/ORIGINALITY

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

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ABSTRACT

Free-piston internal combustion engines found commercial success as air compressors in the 1920's and 1930's, and afterward as gas turbine gasifiers for stationary applications. Since that time they have failed to see commercial application, however in the last decade or so there has been a resurgence of interest in free-piston engines because of their ostensible simplicity and in the flexibility afforded by an unconstrained piston.

This thesis reports the testing and modelling on a free-piston engine by *Pempek Systems Pty. Ltd*. It is an opposed cylinder, electric machine, operating on a two stroke cycle with direct fuel injection. Analysis of experimental cylinder pressure shows that while compression ignition is suitably fast and reliable, the Pempek engine suffers from (among other things) low charging efficiency. The aim of the modelling work is to understand the reasons for this, and to investigate design options for improvement.

A comprehensive, generally applicable 1D gas dynamics engine model has been developed. The important features of this model are described in some detail. While the model builds on existing methods, a number of unique contributions have been made. A chemical equilibrium code was developed which is computationally efficient and flexible. The 1D gas dynamics method is based on a method developed at *Queens University, Belfast* (QUB) in the early 1990's but has been thoroughly re-worked in the way it handles friction, gas property changes and heat transfer. The originally first order accurate method has been changed to second order, and a way of preserving full mass conservation has been developed. An unsteady heat transfer model is proposed. A comprehensive boundary solution is presented, which has relevance to all 1D gas dynamics models. The gas dynamics model is validated against extensive single shot data from QUB, and also against some experimental engine-run data.

The 1D gas dynamics engine model is used to assess the viability of utilising exhaust pipe tuning to drive the charging process of the Pempek engine. Simulation results show that it is possible to charge the engine using exhaust gas dynamics alone.

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PREFACE

At a stand at the World Energy Congress 2004 in Sydney I met Bert Van Der Broek and Edward Wechner and was introduced to the Pempek free-piston engine. Ed explained to me the fascinating features of his new engine design and invited me to visit the workshop to see some prototype testing. This was the start of my association with Pempek Systems, which lead to a final year project exploring the scavenging of the engine, then on to this PhD in a similar vein.

Pempek Systems had done what few research groups had yet achieved – they had built and run a full scale electric free-piston engine, demonstrating unequivocally that generator based piston motion control was accurate and robust. Their working prototype was an excellent platform from which to launch a theoretical investigation - which was aimed at providing tools to interpret results, and doing predictive modelling to guide future directions of the project.

A little should be said about the contents of this thesis which follow from the requirements of the project. There are two main topics addressed. The first is the developing technology of free-piston engines. This is the subject of the first two chapters. The second topic is that of engine modelling and makes up the middle part of the thesis. Even though the modelling was developed for the Pempek project, it is nonetheless broadly applicable to all IC engines and even to other fields. Thus, the sections on modelling can be read profitably without concern for the preceding chapters on free-piston engine technology. Likewise, readers with little interest in physics and methods of modelling will be able to read the sections reporting free-piston engine technology. The final section of the thesis takes the engine model and looks at two possible design variations for the Pempek engine.

- Synopsis -

Chapter 1 - Free-piston Engines – overview of developments
Surveys the current state of the art in free-piston engine technology. The survey shows that despite the relative immaturity of the field, promising solutions have been found for the main difficulties, such as piston motion control.

Chapter 2 - Pempek free-piston engine – details and experimental results
Describes the Pempek free-piston engine project in some detail, highlighting the successful piston motion control, and describing some of the difficulties that were faced, in particular low combustion energy and high compressor power

consumption. In order to explore the potential for lower compressor pressure, it was deemed necessary to analyse the gas dynamics of inlet and exhaust systems. This is the motivation for the modelling work which follows.

Chapter 3 - Thermodynamic and gas property models

Describes three key components of the engine model – namely the single zone thermodynamic cylinder model, the gas property model and the chemical equilibrium model.

Chapter 4 - Unsteady 1D gas dynamics model

Describes the unsteady gas dynamics model, which was based on an existing method, but with several modifications. Concludes with some simple validation cases.

Chapter 5 - Other sub models

Describes miscellaneous other parts of the engine model which were not covered in the previous two chapters.

Chapter 6 - The engine model – integrating all sub models

Explains the integration of all the sub models into the overall engine model

Chapter 7 - Validations using experimental results

Validates the gas dynamics model against a suit of single shot experiments, and also a superficial comparison to measured data from the Pempek engine.

Chapter 8 - Predictive modelling

Applies the gas dynamics model to the original Pempek engine but with a modified low pressure compressor, and a tuned exhaust pipe. Simulation results show that low compressor pressure operation is possible. Next, a radical design modification is proposed, and the gas dynamics model is used to test the viability of un-boosted charging. These two applications of the gas dynamics model demonstrate the usefulness of the model, and the sort of design options that are available for free-piston engines to take advantage of gas dynamics to improve and control charging.

Chapter 9 - Summary and conclusion

Summarises the specific findings for the Pempek project, summarises the model scope and usefulness, and lists the unique contributions of the thesis. A list of suggested further work is also included.

Appendices

A wide range of material with further details of free-piston engine projects and the engine model.

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NOMENCLATURE

Symbols

A	area (m^2)
a	speed of sound (m/s)
a_0	isentropic reference speed of sound (m/s)
a	acceleration (m/s^2)
$a\mathrm{A}$	moles of atomic element i.e. $a\mathrm{C}, a\mathrm{H}, a\mathrm{N}, a\mathrm{O}$ (mol)
C	circumference or wetted perimeter of a duct (m)
C_f	Coefficient of friction (Fanning friction factor) (-)
C_h	Coefficient of heat transfer (W/m^2/K)
C_p, C_v	specific heat at constant pressure and constant volume (J/kg/K)
$\hat{C}_p, \hat{C}_v$	specific heat at constant pressure and constant volume (J/mol/K)
C_p^*, C_v^*	frozen specific heats (see Appendix II) (J/kg/K)
c	wave velocity (m/s)
$D_h = \frac{4A}{C}$	hydraulic diameter (m)
F	force (N)
$H, \dot{H}$	Enthalpy, enthalpy flow rate (J, J/s)
$h,\ \hat{h},\ \Delta\hat{h}^o$	specific enthalpy, enthalpy of formation (J, J/kg, J/mol)
k	thermal conductivity (W/m/K)
L	Length
L_∞	Large eddy length
M	momentum (kg.m/s)
M	molar mass (g/mol)
$m,\ \dot{m}$	mass, mass flow rate (kg, kg/s)
$\mathcal{N}$	Total mixture moles (mol)
n_s	Species moles (mol)

P, P_0	pressure, reference pressure (absolute pressure, Pa)
$\dot{Q}, \dot{q}$	heat transfer rate (J/s, J/kg/s)
R	gas constant (J/kg/K)
$\hat{R}$	universal gas constant (8.314472 J/mol/K)
Re, Re_t	Reynolds Number, turbulent Reynolds number (-)
T	temperature (K)
T_0	isentropic reference temperature (K)
t	time (s)
u, u_0	fluid velocity, quiescent fluid velocity (m/s)
u'	turbulence intensity, RMS of fluctuating velocity (m/s)
$U, u, \hat{u}$	internal energy, specific internal energy (J, J/kg, J/mol)
v	velocity (m/s)
V, v	volume, specific volume (m^3, m^3/kg)
$\dot{W}, \dot{w}$	work rate (J/s), specific work rate (J/kg/s),
$X = \left(\frac{P}{P_0}\right)^{\frac{\gamma-1}{2\gamma}}$	pressure amplitude ratio (-)
y_s	species mole fraction (-)
$\gamma = \frac{C_p}{C_v}$	ratio of specific heats (-)
$\gamma^* = \frac{C_p^*}{C_v^*}$	ratio of frozen specific heats (-)
μ	viscosity (N.s/m^2)
ν	Courant number (-)
ρ	density (kg/m^3)
[CO], [CO2] etc	species molar concentration (kmol/m^3)

Subscripts

L	leftward
R	rightward
i	iteration, incident
f	flow
$prev$	previous
r	reflected
s	species

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ACRONYMS

BDC	Bottom dead centre
BTDC	Before top dead centre
CFD	Computational Fluid Dynamics
FPEC	Free-piston Energy Converter, project name for a European free-piston engine consortium
HCCI	Homogenous Charge Compression Ignition
IMEP	Indicated mean effective pressure
QUB	Queens University Belfast
TDC	Top dead centre
WRT	With respect to

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