Applied Thermal Engineering 42 (2012) 145–153

Contents lists available at SciVerse ScienceDirect

Applied Thermal Engineering

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

Heat transfer processes in parallel-plate heat exchangers of thermoacoustic devices – numerical and experimental approaches

Artur J. Jaworski [a,*], Antonio Piccolo [b]

[a] Department of Engineering, University of Leicester LE1 7RH, University Road, United Kingdom
[b] Department of Civil Engineering, University of Messina, Contrada di Dio – 98166 S. Agata (Messina), Italy

ARTICLE INFO

Article history:
Received 21 November 2011
Accepted 8 March 2012
Available online 15 March 2012

Keywords:
Heat transfer
Heat exchangers
Thermoacoustic engines and coolers
Oscillatory flow
Experimental
Numerical

ABSTRACT

This paper addresses the issues of heat transfer in oscillatory flow conditions, which are typically found in thermoacoustic devices. The analysis presented concerns processes taking place in the individual "channels" of the parallel-plate heat exchangers (HX), and is a mixture of experimental and numerical approaches. In the experimental part, the paper describes the design of experimental apparatus to study the thermal-fluid processes controlling heat transfer in thermoacoustic heat exchangers on the micro-scale of the individual channels. Planar Laser Induced Fluorescence (PLIF) and Particle Image Velocimetry (PIV) techniques are applied to obtain spatially and temporally resolved temperature and velocity fields within the HX channels. The temperature fields allow obtaining the local and global, phase-dependent heat transfer rates and Nusselt numbers, and their dependence on the Reynolds number of the oscillating flow. The numerical part of the paper deals with the implementation of CFD modelling capabilities to capture the physics of thermal-fluid processes in the micro-scale and to validate the models against the experimental data. A two-dimensional low Mach number computational model is implemented to analyse the time-averaged temperature field and heat transfer rates in a representative domain of the HXs. These are derived by integrating the thermoacoustic equations of the standard linear theory into a numerical calculus scheme based on the energy balance. The comparisons between the experimental and numerical results in terms of temperature and heat transfer distributions suggest that the optimal performance of heat exchangers can be achieved when the gas displacement amplitude is close to the length of hot and cold heat exchanger. Heat transfer coefficients from the gas-side can be predicted with a confidence of about 40% at moderate acoustic Reynolds numbers.

1. Introduction

Thermoacoustic technologies are concerned with developing new concepts of engines, coolers and heat pumps which operate on the basis of a range of thermoacoustic effects. These are broadly understood as energy transfer between a compressible fluid and solid boundary in the presence of an acoustic wave. The correct phasing between the acoustically-induced fluid displacement and its compression or expansion, coupled with heat transfer processes between the solid and fluid, will lead to the implementation of Stirling-like thermodynamic cycles which are of practical engineering importance. A number of practical thermoacoustic devices, both standing- and travelling-wave, have already been demonstrated [1,2].

There are significant advantages of utilising thermoacoustic technologies, in certain areas of application. Firstly, as there are no moving components, the thermoacoustic devices can be around one order of magnitude cheaper than many conventional cycles (e.g. typical Stirling machine) and can offer longevity and low maintenance costs. In addition, as the thermodynamic cycle uses environmentally benign noble/inert gases as the working medium, there are significant environmental benefits of the technology. Finally, thermoacoustic systems scale very well and are ideal for utilising the low grade heat input (waste heat from industrial processes and solar energy and other forms of energy harvesting) which offers new opportunities for energy conservation.

A typical thermoacoustic device consists of (i) an acoustic network, (ii) an electro-acoustic transducer, (iii) a porous solid medium (namely a regenerator in travelling-wave systems [3] or a stack in standing-wave systems [4]) and (iv) at least a pair of heat exchangers (HXs) [5]. The stack/regenerator is the component where the desired heat/sound energy conversion takes place. "Hot" and "cold" heat exchangers (CHX and HHX, respectively), placed in close proximity of both ends of the stack/regenerator, absorb (or

* Corresponding author. Tel.: +44 (0) 116 223 1033; fax: +44 (0) 116 252 2525.
E-mail addresses: a.jaworski@le.ac.uk, a.jaworski@yahoo.co.uk (A.J. Jaworski).

1359-4311/$ – see front matter © 2012 Elsevier Ltd. All rights reserved.
doi:10.1016/j.applthermaleng.2012.03.014