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Numerical correlation for the pressure drop in Stirling engine heat exchangers

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New correlation equations, to be valid for the pressure drop and heat exchange calculation under the developing transitional reciprocating flow encountered in Stirling heat exchangers are numerically derived. Reynolds-Averaged Navier–Stokes (RANS) equations based turbulence models are used to analyse laminar to turbulent reciprocating flow, focussing on the onset of turbulence and transitional reciprocating flow regime. The relative performance of four turbulence models in more accurately capturing the characteristics of the flow of interest is assessed in relation to overcoming the problems identified in previous numerical studies. The simulation results are compared with published and well-known experimental data for reciprocating pipe flows, indicating that the effects of the turbulence anisotropy need to be taken into account in order to accurately predict the laminar to turbulent transition. The anisotropic Reynolds stress turbulence model is selected as a best choice among the tested turbulence models for analysis of this transitory phenomenon based on the comparative qualitative and quantitative results. This model is used to evaluate the heat transfer and pressure drop and propose new correlations considering the working and dimensional characteristics of Stirling heat exchangers: $100 \leq Re_\omega \leq 600$, $A_0 \leq 600$, $\beta_{cri} > 761$ and $40 \leq L/D \leq 120$. These correlation equations reduce the unsteady 2D behaviour in reciprocating pipe flow into a manageable form that can be incorporated into Stirling engine performance codes. It is believed that the validated numerical model can be used with confidence for studying the transitional reciprocating flow and the obtained correlations, can be applied as a cost effective solution for the development of Stirling engine heat exchangers.

1. Introduction

Combined heat and power (CHP) is a technology known to allow primary energy savings and therefore reduced CO_2 emissions in line with the goals of the European Union [1]. Focussing on the demand of renewable resources, a sustainable growth based on efficient technologies that can operate with different green energy sources is promoted, being the Stirling engine based CHP one of the most promising technologies [2,3]. The Stirling engines have suitable applications including conversion of solar energy, co-generation, submarine and space applications.

Among the different components of Stirling engines, heat exchangers are identified as an important component in the performance of the overall system [4]. The optimization of the heat exchangers focuses on reducing pressure losses and increasing the heat transfer capacity. Recent studies have focused on the characterization of this phenomenon [5] as it is crucial in CHP applications to maximize the ratio between generated electrical power and source energy input [6].

Correlations for the calculation of the friction factor and Nusselt number under the reciprocating flow conditions encountered in Stirling machines have not been published until recent years. The common practice has been that the correlations derived from steady-state unidirectional flow are used [6,7] since no correlation has been available for reciprocating flow conditions [8]. Different authors have remarked the need of new

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Nomenclature

A_0	Dimensionless oscillating amplitude of the fluid, x_{max}/D or $2Re_\omega Re_{max}$
c_f	Fanning friction factor
D	Pipe diameter
f_μ, f_a, f_b	Low Reynolds number functions
TI	Turbulence intensity
k	Turbulent kinetic energy
L	Pipe length
Le	Entrance length
Nu	Nusselt number
p	Pressure
r	Radial coordinate direction
R	Pipe radius
Re	Reynolds number, $\rho u D/\mu$
Re_ω	Kinetic Reynolds number, $\rho\omega D^2/\mu$
t	Time
TI	Turbulence intensity
u	Velocity component
U_0	Amplitude of the cross-sectional mean velocity, $A_0 Re_\omega \mu/2\rho D$
y^+	Dimensionless distance from the wall

Greek symbols

β	Dimensionless parameter indicator of reciprocating flow type, $A_0\sqrt{Re_\omega}$
ε	Dissipation rate
θ	Crank angle
μ	Dynamic viscosity
μ_t	Turbulent viscosity
ρ	Density
τ	Shear stress
ϕ	Phase lag between wall shear stress and cross-sectional mean velocity
ω	Angular velocity of the bulk flow oscillation

Superscripts

‘	Fluctuating part
$\bar{}$	Average quantity

Subscripts

cri	Critical values of reciprocating flow
i,j	Coordinate directions in index notation
max	Maximum value
min	Minimum value
w	Value at the wall

correlations for determining these quantities when modelling Stirling engines [9,10].

Seume and Simon [11] examined different Stirling engines and presented the working conditions in terms of dimensionless similarity parameters, revealing that most Stirling engine heat exchangers operate in the transitional and turbulent flow regime. This compilation is shown in Fig. 1 according to the two similarity parameters chosen by Zhao and Cheng [12], the kinetic Reynolds number, Re_ω, and the dimensionless oscillating amplitude of the fluid A_0.

Fully developed laminar reciprocating flow was first studied experimentally by Richardson and Tyler [13] discovering the so-called “annular effect”, i.e., the peak in the velocity profile moves towards the pipe wall at sufficiently high oscillation frequency. The analytic flow solution corresponding to the Richardson and Tyler study was obtained subsequently by Sexl [14], Womersley [15] and Uchida [16].

Akhavan et al. [17] experimentally investigated the transition of oscillating flows in circular pipes. They verified the theoretical solutions of Womersley [15] and Uchida [16] obtaining good agreement as previously did Ohmi and Iguchi [18]. Seume et al. [19] performed experiments to observe the behaviour of reciprocating flow during transition. Data on fluid velocity and root mean square, rms, velocity fluctuations were taken using hot film anemometry

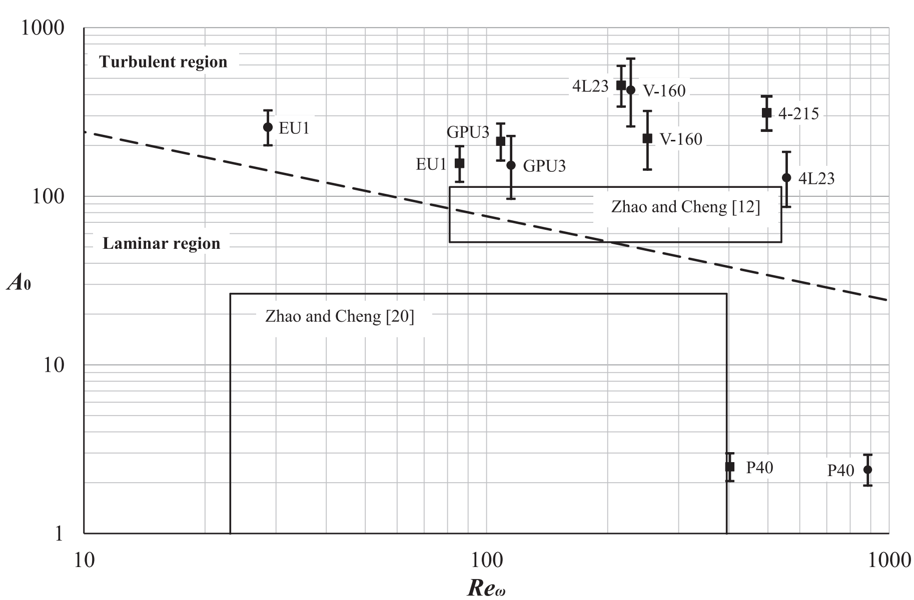

Fig. 1. Stirling heat exchangers working range, A_0 vs. Re_ω.