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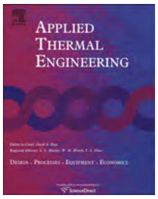

Oscillating flow in a stirling engine heat exchanger

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ABSTRACT

Three heat exchangers exist in modern Stirling engines: a heater, a cooler, and a regenerator. Here a study that deals principally with tubular heaters and coolers is carried out. The calculation procedure for the oscillating flow heat transfer is presented. Literature sources are studied to find the most suitable correlations by comparing them to each other and to the classical turbulent flow correlations encountered in the literature. The enhancement of heat transfer by means of a few circumferential slots inside the tubes and the pressure losses of oscillatory flow are discussed. Non-circular cross-section conduits with rectangular and triangular cross-sections are investigated and compared to the smooth circular tubes. The increment of the performance of an idealised Stirling engine with slotted heat exchanger tubes is compared to the case with smooth ones. The ratio of the gain in the shaft power and pumping losses is 2.22. The Carnot efficiency increment is 2.7%.

1. Introduction

Convective heat transfer equations for oscillating flow encountered in Stirling engines have not been published until recent decades. The common practice has been that the turbulent correlations, e.g. the Dittus–Boelter equation [1,2], are used since ‘no correlations existed up to now to calculate the heat transfer coefficient and friction factor in oscillating flow’ [3]. Turbulence takes time to form and settle and the picture to date is quite complex when heating and pressure variation are added. In the fully turbulent and fully laminar range the steady unidirectional approximations are fairly good [4]. The laminar range is covered well in the latest papers in terms of oscillating convective heat transfer. In the literature survey several papers were found about heat transfer for the oscillating pipe flow encountered in Stirling engine heat exchangers. In this study they are compared to three classical unidirectional flow equations (Table 1).

As early as 1929 Richardson and Tyler [5] discovered the so-called ‘annular effect’ in an oscillatory flow in a pipe, i.e. the maximum velocity in an oscillatory flow occurs near the wall rather than at the centre of the pipe, as in the case with unidirectional steady flow. This applies especially at higher cycle frequencies [6]. Tang and Cheng (1993) [7] (Eq. (1), Table 1) employed multivariate statistical analysis to obtain an experimental correlation equation for the cycle-averaged Nusselt number in terms of three similarity parameters: Re, Re_{ω}, and the dimensionless fluid displacement A_{ω}. Their experimental runs were performed for air in a heated pipe for the following ranges of parameters: $7 < Re < 7000$; $7 < Re_{\omega} < 180$. and $0.06 < A_{\omega} < 2.21$. On the basis of an experimental and numerical study, Zhao and Cheng (1996) [8] derived Eq. (2), which consists of only two similarity parameters, Re_{ω} and A_{o}. They plotted $Nu/A_{o}^{0.85}$ as a function of Re_{ω} ($0 < Re_{\omega} < 500$), while the dimensionless oscillating amplitude of fluid A_{o} variable got the values 8.5, 15.3, 20.4, and 34.9. De Monte et al. (1996) [9] (3) made a comprehensive analytical study of oscillating heat transfer in Stirling machines regarding the inside and outside heat transfer of the heater, cooler, and regenerator and the effect of heat-exchange effectiveness on the performance of a Stirling engine. They applied the empirical correlation proposed by Tang and Cheng (1993) [7] and suggested that the correlation was valid under the following range of conditions: $11 < Re_{max} < 10{,}995$; $1.75 < Re_{\omega} < 45$. Walther et al. (1998) [6] performed a theoretical analysis to evaluate the influence of developing flow on the heat transfer associated with laminar oscillating pipe flow. Their heat transfer correlation (4) (the integral Nusselt number describing the averaged wall heat transfer as a function of the dimensionless oscillating frequency, the pipe length, and the bulk velocity) was plotted for the range: $1000 \le Re_{max} \le Re_{max}^{trans}$; $50 \le Re_{\omega} \le 900$; $0.2 \le \Lambda \le 900$, where $Re_{max}^{trans} = 400\sqrt{Re_{\omega}}$.

In this study Eqs. (1)–(4) were first tested by numerical calculations in a tubular heat exchanger and then compared to three

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