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Modelling of a two-phase thermofluidic oscillator for low-grade heat utilisation: Accounting for irreversible thermal losses

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HIGHLIGHTS

- ▶ Two models for a novel two-phase thermofluidic oscillator are developed.
- ▶ The effect of including a dissipative thermal loss (TL) parameter is investigated.
- ▶ The models predict the oscillation frequency of a prototype (0.1–0.2 Hz) well.
- ▶ Excluding the TL parameter leads to a 30-fold overestimation of the measured efficiency.
- ▶ Including the TL parameter allows for a much improved prediction of the efficiency.

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ABSTRACT

The Non-Inertive-Feedback Thermofluidic Engine (NIFTE) is a two-phase thermofluidic oscillator which, by means of persistent periodic thermal-fluid oscillations when placed across a steady temperature difference, is capable of utilising low-grade (i.e., low temperature) heat to induce a fluid motion. Two linearised models of the NIFTE are presented in this paper, both containing a description of the phase-change convective heat transfer that takes place between the working fluid and the heat exchangers. The first model (LTP) imposes a steady linear temperature profile along the surface of the heat exchangers; whereas the second model (DHX) allows the solid heat exchanger blocks to store and release heat dynamically as they interact thermally with the working fluid. In earlier work [Solanki R, Galindo A, Markides CN. Appl Therm Eng; [24]] it was found that these models predict the oscillation (i.e., operation) frequency of an existing NIFTE prototype pump well, but significantly overestimate its reported efficiency. Specifically, the LTP and DHX models predicted exergetic efficiencies 11 and 30 times higher than those observed experimentally, respectively. In the present paper, a dissipative thermal loss parameter that can account for the exergetic losses due to the parasitic, cyclic phase change and heat exchange within the device is included in both models in an effort to make realistic predictions of the exergetic efficiencies. The LTP and DHX models, including and excluding the thermal loss parameter, are compared to experimental data. It is found that the inclusion of the thermal loss parameter increases the predicted oscillation frequencies in the DHX model, but has a negligible effect on the frequencies predicted by the LTP model. A more significant effect is observed with respect to the efficiencies, whereby the inclusion of the thermal loss parameter leads to a greatly improved prediction of the exergetic efficiencies of the prototype NIFTE pump by both the LTP and DHX models, both in trend and approximate magnitude. From the results it is concluded that, on accounting for thermal losses, the DHX model achieves the best predictions of the key performance indicators of the NIFTE, that is, of the oscillation frequency and exergetic efficiency of the device.

1. Introduction

For decades conventional power provision has been dominated by heat engines such as internal combustion engines and gas turbines [1]. These energy conversion machines utilise the high-temperature heat released from the combustion of fossil fuels to provide mechanical work for motion or electricity generation, resulting in high thermodynamic efficiencies. However, the world's conventional fossil fuel sources are depleting, leading to ever increasing calls for improvements in the efficiency of traditional devices, plants, processes and systems, as well as the use of alternative, sustainable and clean energy sources where possible and viable [2]. One such energy source whose utilisation has attracted increasing attention is low-grade heat, which can be classed as heat that is available from any source at low temperatures (up to

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$\sim$250 °C [3]). Although the use of low-grade heat is associated inherently with low Carnot (and hence also, actual) efficiencies, it is ubiquitous and abundantly available; from the waste heat that is rejected from industrial processes, to solar energy and geothermal heat [4].

Thermofluidic oscillators are a class of heat engines that are capable of converting low-grade heat into useful work. The term ‘thermofluidic oscillator’ is used generally to describe a heat engine within which periodic thermodynamic (e.g., pressure, temperature), heat and fluid oscillations are induced from *steady* thermal boundary conditions (i.e., the external heat source and heat sink temperatures) [5]. Examples of thermofluidic oscillators include gas-cycle thermoacoustic engines [6–9], liquid-piston Fluidyne engines [10–12], free-piston Stirling engines [13,14], and pulse-tubes [15–17].

A thermofluidic oscillator consists of compartments and interconnections that contain a working fluid, while typically featuring no (or few) moving mechanical parts. The working fluid is exposed to an externally imposed temperature difference that is established by a pair of heat exchangers; hot (interfacing with the heat source) and cold (interfacing with the heat sink). The temperature difference gives rise to alterations between successive heat addition and rejection, at the hot and cold heat exchangers. The volume oscillations that arise, lead, in turn, to an oscillatory, periodic fluid displacement (motion).

The main feature of thermofluidic oscillators that is of particular interest in the current work concerns their ability to operate across small temperature differences between the heat source and sink, making them ideal devices for the conversion of low-grade heat. The use of low-grade heat makes thermofluidic oscillators inherently inefficient compared to their high energy counterparts. However, the low (or zero) cost of their energy source, together with their increased reliability from the lack of mechanical moving parts, result in the advantages of lower operating and maintenance costs [1].

A particular *two-phase* (or, vapour-cycle) thermofluidic oscillator realisation that involves the alternating phase change of the working fluid, and known as the Non-Inertive-Feedback Thermofluidic Engine (NIFTE), was presented by Smith [5,18,19]. The working fluid in the NIFTE concept exists simultaneously in both the vapour and liquid phases, and experiences periodic phase change during operation by evaporation during the heat addition stage and condensation during the heat rejection stage. A simplified schematic diagram of a NIFTE device is shown in Fig. 1a, where it can be seen that the NIFTE consists of two vertical cylinders connected by two horizontal tubes. One of the two vertical cylinders (the displacer; denoted by ‘d’ in Fig. 1a) contains the hot and cold heat exchangers (HHX and CHX, respectively; denoted by ‘th’ in Fig. 1a) necessary for operation. The idealised thermodynamic cycle undergone in the NIFTE can be seen in Fig. 1b. It is noted that the complete cycle takes place inside the two-phase saturation region of the working fluid.

The HHX and CHX provide the external temperature difference necessary to drive the vapour–liquid phase change of the working fluid in the NIFTE. The oscillatory fluid flow that occurs in the power cylinder (‘p’ in Fig. 1a) as a result of this periodic phase change creates an inwards suction and a subsequent outward positive displacement of liquid in the load line (‘l’ in Fig. 1a), thus creating the desired pumping motion in the load. The change of phase of the working fluid during operation requires only a small temperature difference between the HHX and CHX for operation.

An early prototype of the NIFTE, which took the form of a positive displacement (liquid-piston) water pump that used *n*-pentane as its working fluid [5], was reported to operate across a temperature difference of as low as 30 K between the heat source and sink, with the temperature of the heat source being well within the limits of low-grade heat [20]. When operating with a 45–150 W heat source at 65–90 °C (via Joule heating in an electrical element embedded in the HHX), a heat sink at 4–12 °C (via the circulation of pumped cooling ice-water through the CHX) and with *n*-pentane chosen to be the working fluid with a saturation temperature of 36 °C at the pumped pressure of (around and close to) $\sim$1 atm (as in Fig. 1b), this prototype achieved thermal efficiencies up to a little less than 1% and exergetic efficiencies (the thermal efficiency as a fraction of the Carnot efficiency) up to 1.7% [5]. These efficiency values achieved by the early NIFTE prototype can be considered low when compared to: (i) the high thermal efficiency from a standing-wave heat engine of 18.4%, reported by Backhaus and Swift [21] as recorded by Jin using the apparatus described by Godshalk et al. [22]; (ii) the travelling-wave heat engine of Backhaus and Swift [21] that reported exergetic efficiencies of up to 41%; and (iii) the efficiencies associated with Fluidyne engines, typically around 3–4%, but as high as 7% for some larger engines. Clearly, there is ample space for improvements to be made that can allow the NIFTE technology to achieve considerably higher efficiencies than those attained by the early prototype. In order to determine an improved design for a NIFTE device, several models for the NIFTE have been developed [5,18–20,23,24], which can readily account for changes in design, such as device configuration and choice of working fluid.

A dynamic linear temperature profile (LTP) model for the NIFTE was first presented in Refs. [5,18,19]. This model involved compartmentalising the NIFTE device into suitable sections, and developing spatially lumped, linearised first-order sub-models for each component section. Analogies were then drawn between the governing equations of each sub-model and linear passive electrical components, such as resistors, capacitors and inductors [25]. The component sub-models were interconnected to form an electrical circuit representation of the device, similar to that shown in Fig. 5. A similar approach had been used previously to model other thermofluidic oscillators and was shown to be effective in capturing the device behaviour to first-order [9,21,26]. Further, the first model of the NIFTE presented in Refs. [5,18,19] assumed a steady linear temperature profile along the height of the heat exchangers in the thermal domain, such as that shown in Fig. 3a, and neglected all inertial effects of the working fluid in the liquid phase. In some regions of the parameter space, this model gave reasonable predictions of the oscillation frequency and exergetic efficiency observed in the NIFTE prototype, though in other cases the predictions deviated significantly from experimental results [18,19,23].

In the original models of the NIFTE in Refs. [5,18,19] it was assumed that flow inertia could be neglected when modelling this device. However, it is known that the working fluid in the liquid phase has a finite density, which should affect the behaviour of the device. Therefore, Solanki et al. [23] and also Markides and Smith [20] investigated the effect of introducing an explicit description of liquid flow inertia in the original non-inertive model from Refs. [5,18,19]. The revised model presented in Refs. [20,23] that included inertia was termed the ‘inertive’ LTP model. The authors proceeded to compare results from the inertive and original non-inertive LTP models. It was found that the inclusion of inertia led to more realistic predictions of the oscillation frequency of the NIFTE and of the critical temperature difference required in the heat exchangers for operation. It was concluded that improved models of the NIFTE should include a description for the liquid flow inertia.

The heat transfer processes in the NIFTE are one of the most important aspects of the device, and are not well understood due to the complex nature of two-phase heat transfer. As mentioned, the LTP model assumes a linear temperature profile along the height of the heat exchanger blocks, which may be a reasonable approximation. However, this description allows an indefinite