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Working fluid selection for a two-phase thermofluidic oscillator: Effect of thermodynamic properties

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HIGHLIGHTS

- Thirty-one working fluids are investigated using a previously-validated NIFTE model.
- Key fluid properties are the volume of vaporisation and maximum saturation pressure.
- The maximum thermal efficiency of an ideal two-phase displacement cycle is 14–15%.
- The maximum thermal and exergy efficiencies of the NIFTE are 1–2% and 6%.
- R123, R142b, R245ca, butane, pentane, hexane are promising fluids depending on operating conditions.

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ABSTRACT

The Non-Inertive-Feedback Thermofluidic Engine (NIFTE) is a device capable of utilising low-grade heat to produce pumping work. An investigation on the applicability of different working fluids for the NIFTE is presented, with emphasis on the effects of key thermodynamic properties of the working fluid on: (i) the maximum thermal efficiency of an idealised two-phase positive-displacement cycle, and (ii) a prediction of the exergy efficiency of the NIFTE. The properties with the most dominant role in determining these efficiency measures were the change in specific volume due to vapourisation and the maximum saturation pressure in the cycle (linked to the pumping head during operation). Thirty-one pure working fluids were studied using a model of the NIFTE that features a dynamic heat exchanger description and a mechanism to account for thermal losses, presented in earlier work. For the scenario where the maximum cycle pressure was defined by the pumping application, higher efficiencies were predicted for wet and isentropic fluids. For the scenario where the hot and cold heat exchanger temperatures were set by the external heat source and sink, higher efficiencies were predicted for dry and isentropic fluids. The maximum pumping pressure and heat source temperature had non-monotonic effects on the efficiencies exhibited by different working fluids, which were linked to the role of molecular weight and polarity in determining the saturated vapour pressure during evaporation. For a particular NIFTE arrangement, setting and application, an optimum efficiency (and also pumping power output) was attained by selecting a working fluid with a particular maximum cycle (saturation) pressure; in the cases investigated here: 6% at 3.5 bar. Upper bound thermal efficiencies of 14–15% were predicted for the 'best' working fluid undergoing an ideal generalised two-phase positive-displacement cycle, whereas valve and thermal losses in the NIFTE allowed values no higher than 1–2%.

1. Introduction

In recent years there has been a growing interest in improving efficiency and reducing emissions via the enhanced utilisation and conversion of low-grade sources of energy, such as (non-concentrated) solar energy and waste heat [1]. These sources of energy are classified as 'low grade' because they are available at low temperatures, relative to the ambient. The conversion of low-grade heat into useful work with the employment of thermodynamic power-cycle systems leads inherently to low thermal efficiencies compared to the use of high-grade (or, high-temperature) heat sources; a limitation imposed by the second law. Yet, low-grade heat is abundantly available, and can be

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accessed readily and at low-cost in most domestic, commercial and industrial settings.

Conventional heat engines are not particularly well-suited to the utilisation of low-grade energy sources, both from technical/operational and economic viability perspectives. On the other hand however, research into various alternative technologies has provided examples of superior systems for low-grade heat conversion [2–6]. As a consequence, a number of relevant cycles and engines are being investigated for this purpose, including a number of Organic Rankine Cycle (ORC) variants and a class of devices known as ‘thermofluidic oscillators’ [7–9].

A generalised thermofluidic oscillator consists of a network of interconnected chambers and tubes, usually without mechanical moving parts. The combined volume within the thermofluidic oscillator is occupied by a working fluid that is subjected to time-varying flow and heat transfer, as the fluid is compressed/expanded and translated within the volume, thus undergoing thermodynamic property variations in an unsteady thermodynamic cycle. The oscillations in the associated processes are driven by a pair of hot/cold heat exchangers that give rise to oscillatory heat addition and rejection. A key feature of thermofluidic oscillators is their ability to use low temperature differences to drive the power cycle, making low-grade heat a suitable power source.

Recent efforts have focused on a device known as the ‘Non-Inertive-Feedback Thermofluidic Engine’ (NIFTE); a two-phase thermofluidic oscillator that has been shown to be able to covert low-grade heat into pumping (hydraulic) work, with the working fluid undergoing phase change during the heat addition/rejection processes [7,10,11]. A pair of hot and cold heat exchangers within the NIFTE are used to impose a periodic addition and rejection of heat to/from the working fluid, which gives rise to alternating phase change, volume and pressure variations, and results consequently in an oscillatory fluid motion during operation that can be harnessed directly via the use of a so-called ‘liquid piston’ (column of liquid) that transmits the hydraulic power to a pumped medium. One of the main features of the NIFTE that sets it apart from most other thermofluidic oscillators concerns the working fluid, which undergoes phase change during operation. As a result, only a small temperature difference between the hot and cold heat exchangers and a small heat exchange surface area are required for significant heat transfer, allowing simpler designs without the need for extended heat transfer surfaces and a lower-cost system.

ORC systems [12,13] are a relatively mature technology capable of utilising low-grade heat, while Fluidyne engines (also referred to as ‘liquid-piston Stirling’ engines) [14,15] are also able to utilise low-grade heat, by converting this directly into pumping work. The former is suitable for the conversion of heat to electricity, and is based on a conventional Rankine cycle but incorporating an organic working fluid, whereas the latter is based on an inherently unsteady thermodynamic cycle whereby heat is converted into pumping by a pulsating/oscillatory motion and with the use of a liquid piston, in a similarly way to the NIFTE. The main difference between the Fluidyne engine and the NIFTE is that the Fluidyne is based on a single-phase (gas) cycle that is used to displace a liquid (the pumped medium), whereas the NIFTE is a two-phase (vapour) engine that relies on the evaporation and condensation of the working fluid. A further difference arises from the inherent reliance of the Fluidyne on a tuning line, which leads to added mass and an increased size. Owing to it’s aforementioned characteristics, and the NIFTE’s simple construction, high mechanical reliability and reduced size (and also, importantly, reduced capital investment costs and minimal running costs), the NIFTE promises to become both technically and economically viable in application areas where such fluid pumps are not currently deployed.

The NIFTE is capable of pumping a wide variety of fluids, including sensitive biological cultures and chemically or mechanically abrasive media. It is also capable of utilising solar energy, thus operating with low-cost solar-thermal collectors, and so a particularly viable application for this technology is solar-powered pumping for irrigation, while the resurgence of interest in absorption cycles for thermally driven (e.g. solar-powered) refrigeration, cooling and air-conditioning, promises to establish another important application area that would be an excellent match for the NIFTE technology [16]. Furthermore, a recent study has demonstrated the potential of this technology for use as a hot water circulator in central heating systems [17].

A number of linear dynamic models for the NIFTE have been presented in previous work, all of which use an approach based on electrical analogies for model development [7–11,18,19]. In these approaches spatially lumped and first order linear sub-model representations of the individual components of the NIFTE device are modelled by linear passive electrical components (resistances, capacitors and inductors) and interconnected in an electrical circuit/network representation of the entire device. Specifically, viscosity, fluid drag and thermal resistance are taken into account by including resistances, whilst gravity and vapour compressibility are accounted for by capacitors, and fluid inertia by inductors. One of these models for the NIFTE, namely the dynamic heat exchanger model with thermal loss ($\mathrm{DHX_{TL}}$), which is described briefly in Section 2.2 (refer to Refs. [18,19] for more detail), takes into account the ability of the hot and cold heat exchanger blocks to store and release energy (in the form of internal energy) as they interact thermally with the working fluid. This model also accounts for a form of parasitic condensation and heat losses that have been observed in the device [19].

The NIFTE $\mathrm{DHX_{TL}}$ model was successfully validated against experimental data in Ref. [19], where it was found to be the best representation of a NIFTE prototype water pump presented earlier in Ref. [7]. The working fluid used in the prototype NIFTE pump was *n*-pentane, whose saturation temperature at atmospheric pressure is 309.21 K (36.06 °C). It is important to note that all previous investigations on the NIFTE have been based on *n*-pentane as the working fluid [7,10,11]. Although, this is a relatively common working fluid for use in thermodynamic power-cycle systems using low-grade heat [20–23] and matches the experimental work performed on the NIFTE prototype, other organic fluids have also been shown to perform well (often significantly better than *n*-pentane) in many low-grade heat-driven applications, and so it is important to understand the role that the working fluid can have in the operation and performance of the NIFTE device. This is focus of the present paper.

There are currently numerous publications on working fluid selection for ORCs [20,22–24]. A review of 35 fluids by Chen et al. [20] showed that it is challenging to find a ‘best’ working fluid across a range of heat source temperatures. This finding is confirmed by many similar studies in the literature, which suggests that it is difficult to generalise selection rules and knowledge concerning the use and performance of working fluids across different cycles and operating conditions. Nevertheless, the critical temperature of the working fluid and the slope of its saturated vapour curve were identified as important criteria to take into account when determining the type of cycle and operating temperature of the working fluid. Another study on the selection of a working fluid for an ORC in a biomass heat and power plant was carried out by Drescher and Brüggerman [24]. Contrary to common ORC systems driven by low-grade heat, a higher source temperature of 600 K (≈330 °C) was considered in this study. The best working fluids were found to be in the alkylbenzene family. Further, the study carried out by Madhawa Hettiarachchi et al. [22] investigated four working fluids for use in an ORC with low-temperature