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# Working-fluid selection and performance investigation of a two-phase single-reciprocating-piston heat-conversion engine

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## HIGHLIGHTS

- A dynamic model of the Up-THERM two-phase thermofluidic oscillator heat converter is presented.
- The working-fluid saturation pressure and vapour-phase density are important in describing the engine's performance.
- Water and forty-five organic working-fluids are considered in a pre-specified Up-THERM design with a heat source at 360 °C.
- R113 and *i*-hexane are identified as optimal working fluids in terms of maximizing the engine's power output.
- Ammonia, R245ca and butane are attractive working fluids over a wider range of heat-source temperatures.

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## ABSTRACT

We employ a validated first-order lumped dynamic model of the Up-THERM heat converter, a two-phase unsteady heat-engine that belongs to a class of innovative devices known as thermofluidic oscillators, which contain fewer moving parts than conventional engines and represent an attractive alternative for remote or off-grid power generation as well as waste-heat conversion applications. We investigate the performance of the Up-THERM with respect to working-fluid selection for its prospective applications. An examination of relevant working-fluid thermodynamic properties reveals that the saturation pressure and vapour-phase density of the fluid play important roles in determining the performance of the Up-THERM – the device delivers a higher power output at high saturation pressures and has higher exergy efficiencies at low vapour-phase densities. Furthermore, working fluids with low critical temperatures, high critical pressures and exhibiting high values of reduced pressures and temperatures result in designs with high power outputs. For a pre-specified Up-THERM design corresponding to a target (CHP prime-mover) application with a heat-source temperature of 360 °C, water is compared with 45 other pure working fluids. When maximizing the power output, R113 is identified as the optimal fluid, followed by *i*-hexane. Fluids such as siloxanes and heavier hydrocarbons are found to maximize the exergy and thermal efficiencies. The ability of the Up-THERM to convert heat over a range of heat-source temperatures is also investigated, and it is found that the device can deliver in excess of 10 kW when utilizing thermal energy at temperatures above 200 °C. Of all the working fluids considered here, ammonia, R245ca, R32, propene and butane feature prominently as optimal and versatile fluids delivering high power over a wide range of heat-source temperatures.



## 1. Introduction

Recent trends in global energy use have shown that energy consumption has been increasing, especially amongst developing countries, while, with the exception of the very recent drop in the price of oil, energy prices have been generally rising over the past decades due to a combination of factors, including the growing demand for energy and the gradual reduction in the available reserves of readily accessible fossil fuels [1]. The desire for secure, sustainable, reliable and affordable energy provision in light of increasing energy costs and dwindling resources, along with concerns related to the adverse effects on human health and the environment caused by the release into the atmosphere of gases

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**Nomenclature**

| | |
|---|---|
| $A$ | cross-sectional area ($m^2$) |
| $C$ | capacitance ($m^4\,s^2\,kg^{-1}$) |
| $c$ | geometrical constant (–) |
| $d$ | diameter (m) |
| $F$ | heat transfer coefficient correlation function (–) |
| $f$ | frequency (Hz) |
| $g$ | gravitational acceleration ($m\,s^{-2}$) |
| $H$ | Heaviside step-function (–) |
| $h$ | height (m) |
| $h$ | heat transfer coefficient ($W\,m^{-2}\,K^{-1}$) |
| $h_{fg}$ | enthalpy change during vaporization ($J\,kg^{-1}$) |
| $k$ | spring constant ($N\,m^{-1}$) |
| $L$ | inductance ($kg\,m^{-4}$) |
| $l$ | length (m) |
| $m$ | mass (kg) |
| $P, p$ | pressure (Pa) |
| $P = \dot{W}$ | power output (W) |
| $\dot{Q}$ | heat flow-rate (W) |
| $R$ | resistance ($kg\,m^{-4}\,s^{-1}$) |
| $s_{fg}$ | entropy change during vaporization ($J\,kg^{-1}\,K^{-1}$) |
| $\dot{S}$ | rate of entropy generation ($W\,K^{-1}$) |
| $T$ | temperature (°C, K) |
| $t$ | time (s) |
| $U$ | flow rate ($m^3\,s^{-1}$) |
| $v_{fg}$ | volume change during vaporization ($m^3\,kg^{-1}$) |
| $V$ | volume ($m^3$) |
| $y$ | spatial coordinate (–) |

*Greek letters*

| | |
|---|---|
| $\alpha$ | temperature amplitude (K) |
| $\beta$ | temperature spatial-gradient parameter ($m^{-1}$) |
| $\gamma$ | heat capacity ratio (–) |
| $\delta$ | gap between piston and slide bearing (m) |
| $\epsilon$ | gap between shaft and motor (m) |
| $\eta$ | efficiency (–) |
| $\Lambda$ | non-dimensional expression for $\beta$ (–) |
| $\mu$ | dynamic viscosity (Pa s) |
| $\rho$ | density ($kg\,m^{-3}$) |

*Subscripts*

| | |
|---|---|
| '0' | equilibrium |
| 'acc' | accumulator |
| 'b, l' | slide-bearing liquid |
| 'b, p' | slide-bearing piston |
| 'c' | connection tube |
| 'c' | critical thermodynamic property |
| 'cold' | cold heat-exchanger |
| 'cv' | check valve |
| 'd' | displacer cylinder |
| 'eq' | equilibrium |
| 'ex' | exergy |
| 'g' | gas volume, saturated vapour-phase |
| 'gen' | generator |
| 'gs' | gas spring |
| 'hm' | hydraulic motor |
| 'hot' | hot heat-exchanger |
| 'hs' | heat source |
| 'hx' | heat exchanger |
| 'l' | liquid volume, saturated liquid-phase |
| 'l, d' | liquid height in the displacer cylinder |
| 'load' | load |
| 'lub' | lubricant |
| 'max' | maximum |
| 'min' | minimum |
| 'ms' | mechanical spring |
| 'nl' | non-linear |
| 'pist' | piston |
| 'pv' | piston valve |
| 'q' | heat flux |
| 'r' | reduced thermodynamic property |
| 'sat' | saturation thermodynamic property |
| 'sink' | heat sink |
| 't' | pipe in load |
| 'th' | thermal domain |
| 'v' | vapour volume |
| 'w' | wall |
| 'wf' | working fluid |

produced from the combustion of fossil fuels, have led to an acceleration of efforts aimed at developing alternative, renewable energy sources, including sources of renewable heat such as solar, geothermal, and (arguably) biomass/biogas [1,2].

In addition, a vast amount of low- to medium-grade (*i.e.*, temperature) 'wasted' thermal energy, which is mainly available at significantly lower temperatures than those associated with fossil-fuel combustion (often below 300 °C), is rejected to the environment in the form of exhaust gases, cooling streams, *etc.* This energy resource arises from a diverse and broad range of sources in the domestic, commercial, industrial and transport sectors. Recent estimates indicate that over 60% of the overall primary energy supplied globally is rejected in this form; *e.g.*, 59.0 Quads ($62 \times 10^{18}$ J) of thermal energy was rejected in the US in 2013, which is in excess of the actual national energy consumption (38.4 Quads) by over 50% [3]. Similar figures are reported for Europe and Asia. Therefore, a key component of the energy solution, beyond expanding the utilization of renewable and sustainable energy sources, involves increasing the overall efficiency of fossil-fuel use, thereby reducing both the demand for fossil fuels and the associated emissions. The recovery and re-use of heat has thus been identified as a major pathway towards a high-efficiency and sustainable energy future [1].

Engines capable of utilizing fluid streams at lower temperatures are expected to be inherently inefficient; the Chambadal–Novikov efficiency, $\eta_{C-N} = 1 - \sqrt{T_{sink}/T_{hs}}$ [4,5], for heat-source temperatures below 300 °C drops below 30%, and at heat-source temperatures of 100 °C, it is close to 10%. Despite these low efficiencies, the development and utilization of such engines represents an interesting economic proposition since these would provide a means of reducing the rate at which non-renewable energy resources are being depleted, as well as mitigating any environmental (human or natural) impact associated with the use of these resources. For example, we estimate that recovering and re-using waste-heat streams has the potential to provide an additional 8 EJ of energy towards the annual energy consumption in Europe, thereby reducing the annual primary-energy use by over 15%. This would manifest as a direct reduction of the rate at which fossil fuels are being consumed and at which associated emissions are being produced. This example highlights the important opportunities that exist for suitable technologies that can be deployed for heat recovery, re-use and energy integration, *e.g.*, by conversion to useful mechanical, hydraulic or electrical work. In plants that are already in operation the implementation of various waste-heat recovery technologies can lead to important boosts in overall efficiency and utility expenditure savings [6], and in newly built facilities that