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Research Paper

Modelling and experimental investigation of a thermally driven self-oscillating pump

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HIGHLIGHTS

- A thermally driven self-oscillating pump is presented.
- Experimental analyses to characterize the pump were performed.
- Modelling is based on a non-linear system of coupled differential equations.
- The maximum pump flow rate is 0.0013 kg/s and a 0.25 bar pressure head.
- The thermally driven pump has good potential for aerospace applications.

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ABSTRACT

This paper explores the pumping characteristics and behaviour of a thermally driven self-oscillating pump. The pump consists of a single wickless capillary tube with a circular cross-section. The tube is closed at one end and has a T-section with two check valves at the other end to provide for a one directional flow. An experimental setup was built to investigate the output mass flow and pressure head of the pump. During the experiments, the performance of the check valves had a negative influence on the output mass flow. To determine this influence, a video analysis of the fluid oscillation without the check valves was conducted and compared to results with check valves. The average output mass flow with valves was approximately 0.0010 kg/s with a maximum measured pump flow of 0.0013 kg/s. The maximum pressure head delivered was 0.25 bar. A numerical model of the vapour bubble oscillation was developed to get a better understanding of the pump and its working principles. The model is based on the conservation of mass, momentum and energy, and resulted in a non-linear system of coupled differential equations. Overall, the experiments conducted with the thermally driven self-oscillating pump have shown that the pump has good potential to be used in aerospace applications.

1. Introduction

Thermally driven self-oscillating pumps are simple and robust pumps with a minimum of moving components that operate based on the two-phase oscillation principle of a Pulsating Heat Pipe (PHP). The self-oscillating pump of this study consists of a single wickless capillary tube with a circular cross-section. The tube is closed at one end and has a T-section with two check valves on the other end. The tube is filled with working fluid and is divided into an evaporator, adiabatic and condenser section in analogy with conventional heat pipe terminology. It should be noticed that this terminology is not entirely correct, since condensation may also occur in the evaporator, as shown by Rao et al. [1,2]. An expanding and contracting vapour bubble oscillates between the evaporator and condenser, driven by thermal energy. The vapour bubble acts like a piston, pumping fluid with the aid of the check valves.

The simplicity and robustness of the pump makes it a promising pump for space applications. The current thermal design solutions, such as heat pipes and PHP, are not always able to dissipate heat from many distributed payloads over large distances. Mechanically driven loops overcome this problem, but the sensitivity to wear makes the mechanical pumps in these loops a single point of failure. This paper explores the pumping characteristics and behaviour of a thermally driven self-oscillating pump, as a potential replacement for the mechanical pump in aerospace applications.

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Nomenclature

A	area (m^2)
d	diameter (m)
g	gravity (9.81 m/s^2)
H_{fg}	latent heat of vaporization (J/kg)
L	length (m)
m	mass (kg)
p	pressure (Pa)
p_r	ambient pressure (Pa)
Re	Reynolds number
T	temperature (°C)
t	time (s)
U	heat transfer coefficient (W/m °C)
u	velocity (m/s)
x	position (m)
x_q	vapour quality

Greek letters

θ	contact angle (°)
μ	viscosity (Pa s)
ρ	density (kg/m^3)
σ	surface tension (N/m)

Subscripts

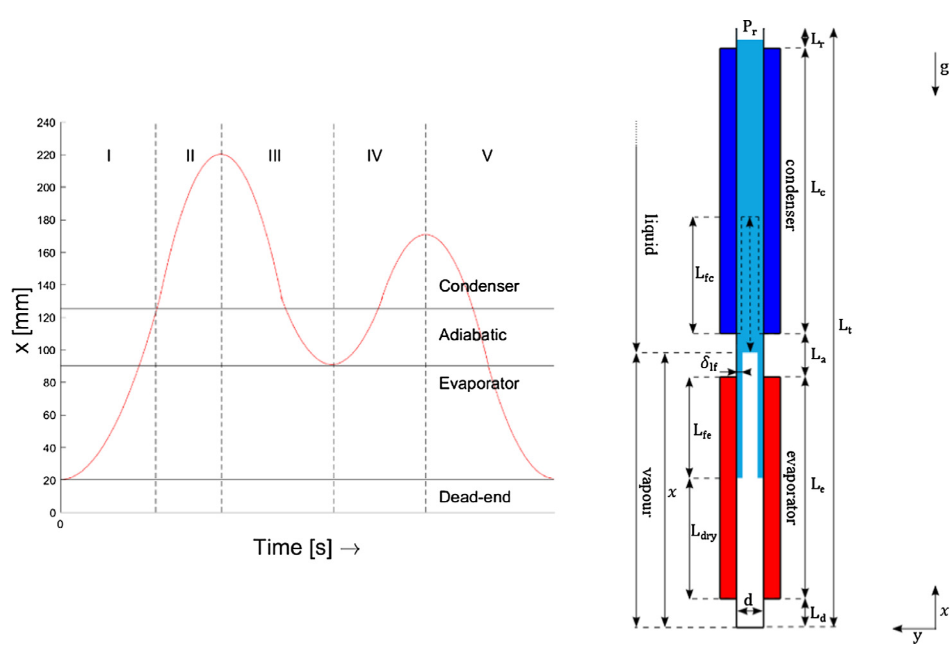
a	adiabatic
c	condenser
d	dead end
e	evaporator
l	liquid
m	meniscus
sat	saturation
t	total
v	vapour

1.1. Pumping principle

The pumping principle of the self-oscillating pump corresponds to the Open Oscillatory Heat Pipe Water Pump (OOHPWP) as constructed by Dobson [3] and is explained according to recent work of Rao et al. [1,2].

The pump working principle is as follows. At the start of each pumping cycle the tube is filled with fluid. The fluid in the evaporator section is heated to the saturation temperature, forming vapour. The ongoing evaporation of fluid, increases the vapour pressure above the ambient pressure. Therefore the meniscus at the liquid-vapour interface starts to move towards the condenser section of the tube (Fig 1a I). The fluid in front of this meniscus is pushed ahead, through the discharge valve. Thereby creating an output mass flow. As discussed by Rao et al., at the start of the meniscus motion, a thin liquid film is deposited on the tube wall behind the meniscus. This thin liquid film is responsible for the major part of the heat and mass exchange, and is the driving force of the pumping motion.

The vapour pressure reaches a maximum just before the meniscus enters the condenser, due to the still evaporating thin liquid film, and the momentum of the liquid plug. The meniscus keeps moving into the condenser (II), despite the decrease of vapour pressure. The vapour pressure decreases due to the expansion and condensation of the vapour bubble. Before the meniscus reaches its topmost position in the condenser, the vapour pressure drops below ambient pressure. This pressure decrease closes the discharge valve and opens the supply valve at almost the same time. Therefore, the last beneficial part of the meniscus stroke towards the topmost position is not used to generate output mass flow. This was observed during the experiments, liquid was forced against the flow, passing through the opened supply valve.



(a) the meniscus position during one cycle

(b) the geometry of the self-oscillating pump model

Fig. 1. Working principle of a self-oscillating pump.