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Research Paper

The development of a sub-atmospheric two-phase thermosyphon natural gas preheater using a lumped capacitance model and comparison with experimental results

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HIGHLIGHTS

- A two-phase thermosyphon is proposed to counteract the Joule–Thomson effect.
- A transient numerical model based on lumped capacitance method is used.
- Experimental and numerical data compared.
- Efficiencies between 68% and 80% are estimated.

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ABSTRACT

The pre-heating of natural gas supplied to both domestic and industrial use is required to counteract the Joule–Thomson effect due to pressure reduction. Most existing pre-heaters are in the form of water bath heaters, where both the burner and exchanger are immersed in a closed water tank. These systems usually have a low efficiency, and as a result of thermal inertia have a long time lag to accommodate changes in Natural Gas (NG) mass flow rates.

In this paper, the two-phase thermosyphon theory is implemented in a sub-atmospheric context to design and study a new preheating system in a transient fashion. This system is partially vacuumed (absolute pressure of 2 kPa) to lower the temperature operation range to reduce the required working fluid volume, hence reduce the required energy and improve the response time. The transient numerical model is based on a lumped capacitance method, and the full system is solved by using a fourth order Runge–Kutta method. The numerical model is validated through comparison with experimental results. Minimum efficiency of 68% has been achieved in some tests, whilst maximum efficiency of 80% in other tests.

Simulations of the thermosyphon preheater system have been performed to analyse the effect of changing the working fluid volume and composition.

1. Introduction

Preheaters are used to heat natural gas prior to reducing compressed flow to ensure no ill effects of the temperature dropping due to the Joule–Thomson effect, such as hydrates forming [1] within the pipe line or valves. If there is any water within the flow, and preheating is not conducted, hydrates can form within the pipes, and build, which can eventually form a plug in the flow.

Within the UK, water bath preheaters are the industry standard, due to a robust and simple design, which has a proven track record; many water baths are still in service after 40 years, but typically last for 25 years. The water bath preheater's design has a burner and a heat exchanger both submerged in the water bath in a single tank. Water bath preheaters have been shown to have relatively low efficiencies, in the region of 40–60% [2]. The UK has legally committed to reducing the carbon footprint by 80% by 2050 [3], and with as many as 1000 preheating sites across the UK that

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need replacing, this provides an excellent opportunity to replace with more efficient preheaters.

A novel preheating system using thermosyphon technology has been developed and is a good replacement for the water bath heater. Thermosyphons use natural convection cycles to transfer heat from a source to a sink, often, but not always, involving phase change, similar in some respects to heat-pipes with some distinct differences [4], see Fig. 1. Thermosyphons with different designs are used in gas turbine blade cooling, water heaters, cooling systems for nuclear reactors and many other cooling applications.

As shown in Fig. 1, the heat source may be on the lower horizontal or vertical sides and the sink may be located at the upper horizontal or vertical sides, yielding different combinations. In this paper, the source and sink are at the lower and upper horizontal sides, respectively.

Smaller thermosyphons have been the subject of extensive research, particularly experimentally. Lin et al. [5] focused on geyser boiling in a vertical annular two-phase closed thermosyphon in an experimental study. Geyser boiling is a phenomenon that happens when a large quantity of the working fluid is ejected from the evaporator to the condenser with high velocity, and therefore oscillatory heat transfer behaviour may exist. This may damage the thermosyphon. The effect of many parameters has been taken into account: the heat load, liquid fill in the evaporator and the condenser temperature. Ethanol and water were used as working fluids. Geyser boiling was shown to occur under low and high heat loads, the period of the geyser boiling is shorter for a higher heat load, a smaller liquid fill, and a shorter evaporator length. A correlation equation was proposed as the mean heat transfer coefficient was found to have an almost linear relationship with the heat input in the logarithmic scale. With ethanol as the working fluid, it was found that geyser boiling occurred in a narrower range of the heat load than with water.

Due to the design and large size (order of metres) of the thermosyphon investigated in this work and the high heat load considered (order of 100 kW), geyser boiling is considered to have little effect on the heat transfer process. The so-called flooding and entrainment limitations, that are present for small size devices, are avoided. The Ledinegg instability [6] is also assumed to be insignificant as the boiling boundary is far from the tube.

Noie et al. [7] considered experimental investigations on a vertical two-phased closed thermosyphon under vacuum using a closed vertical container. Investigations into parameters such as input heat transfer rates, filling ratio of the working fluid and the evaporator lengths were studied to assess the heat transfer performance. It was concluded that the evaporator section was almost isothermal, and that the temperature at the condenser was lower.

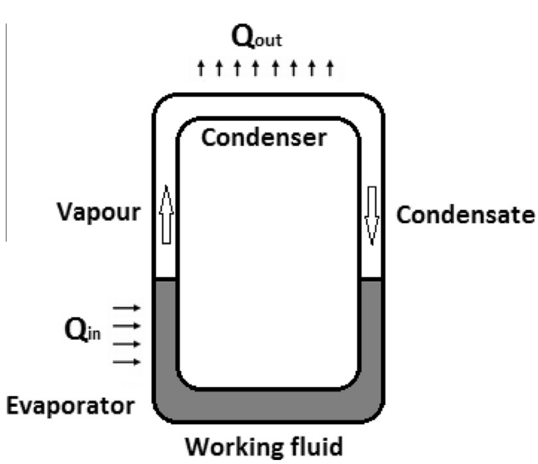

Fig. 1. Diagram of a two phase closed loop thermosyphon.

When the evaporator length was constant, the temperature decreased with an increase in filling ratio to a critical value. With an increase in evaporator length, the critical filling ratio decreased. The maximum heat transfer rates occurred at different filling ratios for each evaporator length.

Garrity et al. [8] employed a small scale two-phase thermosyphon as a cooling system to dissipate the waste heat from proton-exchange membrane (PEM) fuel cells. The maximum heat flux that can be removed from the heated microchannel plate is 32 kW/m^2. Both experiment and simulation were presented. The thermal hydraulic model proposed was based on the pressure change around the flow loop, using gravity, friction and acceleration. HFE-7100 was used as the working fluid. The prediction of the mass flow rate, pressure drop, and microchannel plate thermal field were found to be satisfactory, and the temperature in the plate wall was between 66 and 82 °C.

Jouhara and Robinson [9] considered the performance of a vertical thermosyphon with four different working fluids; water, FC-84, FC-77 and FC-3283. Seven nucleate pool boiling heat transfer correlations were compared to results from experimentation, and found to be in good agreement when water was used as the working fluid. Maximum heat transport capacity was found to be when water was used as the working fluid, except when considering low operating temperatures. This was due to the saturation temperatures of the other working fluids.

Franco and Filippeschi [10] conducted a detailed review into existing experimental studies for a small dimension closed loop two-phase thermosyphon. One of the main findings was that the aims for experiments were often different, therefore, the outcomes were different. The result is that no generalised outcomes could be observed. The implication of the lack of generalised results being that the application of closed loop thermosyphons in different operating conditions is hard to achieve. The complexities involved in conducting experimentation due to highly sensitive equipment were shown, often due to the presence of air.

Many experiments have been carried out for small scale thermosyphon, order of millimetres. Franco and Felippeschi [11] designed an experimental test rig in which they analysed the thermo-fluid dynamic behaviour of CLTPT and in particular the link between heat flow rate and mass flow rate with growing input power ranging approximately from 0 to 1.7 kW and operating pressure between 0.1 and 1 bar. The condenser was about 1 m above the evaporator. Water and ethanol were used as test fluids. The device had a gravity dominated regime with a reduction in the friction dominant regime. Higher instabilities are observed at higher heat loads at which the mass flow rate is reduced from a maximum value. Operating pressure and filling ratio, as shown, has a big impact on the maximum mass flow rate. There is a recommendation to use water at higher loads than ethanol, to avoid critical conditions in the evaporation zone which may arise leading to the occurrence of a second type of instability.

They described in their review [10] the conditions that affect the behaviour of the CLTPT but for small dimensions (order of some millimetres). They analysed the disagreements between the experimental data and the conventional theory developed for an imposed flow rate. They concluded that the fluid flow and the heat transfer mechanisms should be reconsidered in small to micro-channels and should be validated against experiments. In contrast, in large channels in loop thermosyphons, empirical correlations or numerical codes do not take in consideration the effect of flow regime on heat transfer, but preliminary knowledge of the flow pattern such as film flow boiling nucleate boiling and forced convective boiling is necessary. For sub-atmospheric cases, the filling ratio is reported to play an important role.

An experimental study on the performance of a two phase closed loop thermosiphon using different fill ratios of the working fluid