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Article

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An indirect heating solution to reduce CO_2 emission and improve efficiency of gas distribution networks

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ABSTRACT

The gas industry relies on indirect heating to prevent gas from freezing when it is transferred from high-pressure networks to lower pressure distribution systems. The main challenge in preheating natural gas is designing an indirect heating system capable of consistently maintaining a target temperature, despite large load diversity. The most common form of heating technology has traditionally been water bath heaters and boiler houses. In this paper, a novel technology is introduced, and its performance compared to existing installations. The Immersion Tube Thermosyphon Heater was developed specifically to address high load diversity; it combines a high-efficiency immersion burner with a sub-atmospheric two-phase loop thermosyphon. The use of low-temperature steam provides a flexible and precise solution for temperature control easily adapted to variable gas flows. The Immersion Tube Thermosyphon achieved an average thermal efficiency of 90%, considerably higher than the 46% efficient water bath, allowing an estimated annual saving of 7,660 tonnes CO_2 for 1-megawatt gross heat capacity operating with a 50% load factor.

1. Introduction

1.1. Natural gas transportation

Natural gas is transported at high pressures to reduce required pipeline sizes. For delivery to end users, it undergoes expansion and a subsequent temperature drop as a result of the Joule–Thompson effect. To avoid reaching temperatures below freezing post-expansion, the gas is preheated to an appropriate temperature, which depends on the problem's boundary conditions. The main challenge of this task is maintaining the target station outlet temperature for varying gas flows, as shown in Fig. 1.

1.2. Existing indirect heating technology used in preheating

The most common indirect heating technology used on gas distribution networks worldwide is the Water Bath Heater (WBH). Its design is principally based on a fire-tube combined with a natural gas process coil, whereby a heated water/glycol bath is used to indirectly transfer heat to a process coil, as illustrated in Fig. 2.

This simple configuration of a WBH minimises maintenance costs and has been an attractive choice for the gas industry for several decades. The primary drawbacks of WBHs are their low efficiency and lack of precision temperature control due to large system inertia, which can result in imbalances between energy required and energy delivered. Fig. 3 illustrates a three-day temperature and flow profile from a Pressure Reduction Site (PRS/City Gate Station) located in the United Kingdom, whereby a 1.2 MW water bath heater is used to maintain a 2 °C set-point.

As shown, as gas flows undergo transient variations to meet peak morning and evening demand, the WBH is unable to recover in sufficient time to sustain a stable gas temperature after pressure reduction. A common solution to avoid temperatures dropping below safe operating limits for pressure regulation equipment is to increase the station outlet temperature set point. However, higher set points are not desirable as they result in a higher proportion of fuel use, contributing to overheating of natural gas flows beyond that which is beneficial for maintaining safe operating temperatures.

Water bath heaters form part of critical infrastructure installed on gas networks. However, they limit network flexibility in terms of acceptable load diversity due to poor responsiveness and increased carbon intensity from low thermal efficiency. In contrast, thermosyphons were shown to have inherent heat transfer properties that are beneficial to application in preheating, offering potential to overcome limitations of WBHs, particularly where load diversity is high.

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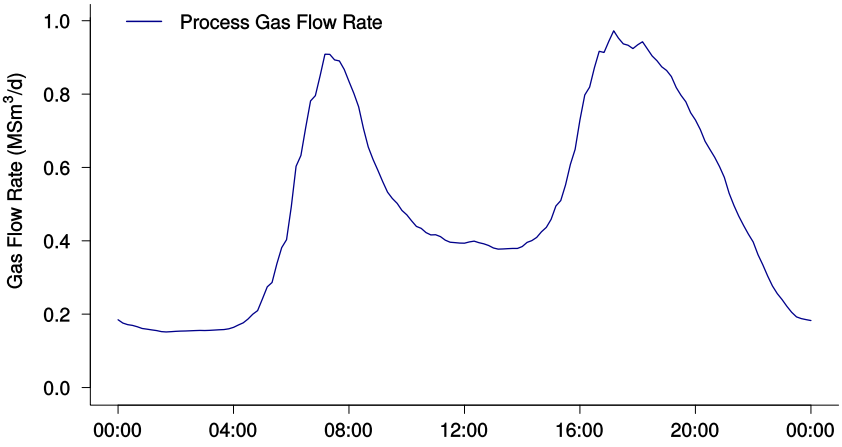

Fig. 1. Gas flow fluctuation for a pressure reducing station (PRS) located in the UK over a 24 h period.

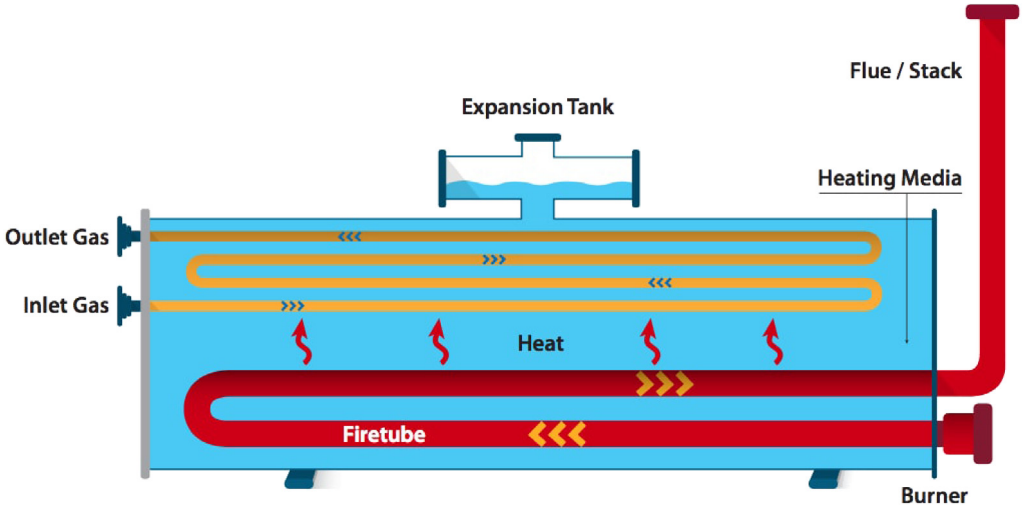

Fig. 2. Diagram of a typical water bath heater used for indirect heating of natural gas.

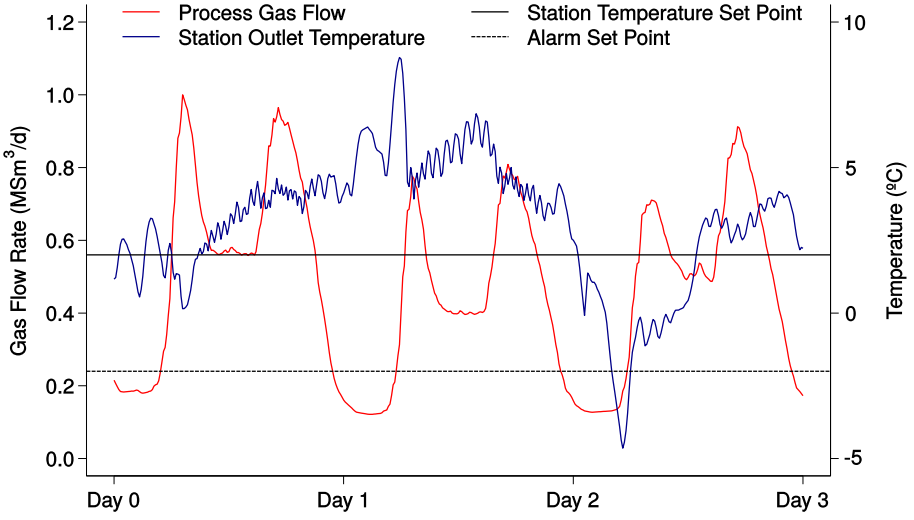

Fig. 3. 1.2 MW water bath heater PRS outlet temperature and gas flow rate over a three-day period.

Fig. 4. Site photo of the immersion tube thermosyphon heater (ITTH).

1.3. Thermosyphon definition

A thermosyphon is a heat transport system with attractive energy saving properties. Heat transport occurs via natural convection, whereby the heat transport fluid is re-circulated by gravity and buoyancy. By relying on a phase-change, the thermosyphon has the capability to transport heat at high rates, without any requirement for external pumping devices. Their high energy-carrying capacity also entails a reduction in the volume of heating media required for a given power, reducing system inertia. Additionally, the process may be assumed isothermal, ensuring low temperature gradients within the system and uniform heat transfer (Sabharwall et al., 2008).

Due to their efficiency and reliability, thermosyphons have been applied in many fields of technology, including, for example, aerospace systems for surface temperature control of satellites, electronic cooling, turbine blade cooling, solar power systems and for heat transport in chemical reactors (Franco and Filippeschi, 2012; Lamaison et al., 2017; Wagner, 2014).

1.4. Sub-atmospheric Thermosyphon – Preheat application

References for a sub-atmospheric thermosyphon used for natural gas preheating can be found in literature, such as Matallah et al. (2016) and Bieliński (2016).

In Matallah et al. (2016), a sub-atmospheric two-phase thermosyphon theory was studied to develop a lumped capacitance model for a new preheating system operating under transient process conditions. The proposed system was partially vacuumed (absolute pressure of 0.02 MPa) to achieve a lower operating temperature and to reduce the required volume of working fluid. Under these conditions, it was possible to achieve increased system efficiency as well as provide a basis for improved load response.

In Bieliński (2016), the experimental validation of a generalised model for a two-phase loop thermosyphon was presented. It was derived from mass, momentum and energy balances of the circulating evaporator, riser, condenser and downcomer. Both theoretical analysis and experimental data were incorporated to form a new variant, which included a thermosyphon loop comprising mini channels and conventional tubes as well as an evaporator on the lower vertical section and a condenser on the upper vertical section. A one-dimensional homogeneous model and a separated two-phase flow model were used in calculations, yielding a strong performance agreement with a laboratory-scale unit.

This paper presents the design philosophy which led to the conception of the Immersion Tube Thermosyphon Heater (ITTH), an alternative indirect heater design to existing single-phase indirect heating technology. Three case studies are considered – two WBHs and one ITTH – with their performance compared and discussed.

2. Experimental apparatus and methodology

This section presents the design philosophy of the Immersion Tube Thermosyphon Heater. The experimental methodology used to assess thermal efficiency is outlined, along with relevant equations and definitions.

2.1. Immersion tube thermosyphon heater (ITTH)

The Immersion Tube Thermosyphon Heater (ITTH) was developed in response to needs articulated by gas distribution networks to resolve problems associated with temperature control and heat transfer efficiency, without compromising asset reliability or lifespan.

The ITTH – depicted in Fig. 4 – is divided into two zones: a hot zone where heat is introduced from the immersion burner to form steam and a cold zone comprising a heat exchanger containing process gas, as illustrated in Fig. 5. The immersion tube burner, developed by ENGIE's research and development team for process fluid heating, was targeted at industrial applications requiring both efficiency and continuity of service.

As steam is produced and rises from the evaporator vessel, energy is transferred to process natural gas by convection in the heat exchanger, whilst gravity and buoyancy ensure the free circulation of fluids between the hot and cold zones. The system uses less liquid, leading to lower thermal inertia, and achieves higher rates of heat transfer by delivering the latent heat of vaporisation to the process gas, with a phase-change occurring between 40 °C and 80 °C under vacuum in the heat exchanger. The high energy carrying capacity of steam under vacuum is quantified in Fig. 6. Note that the system can be assumed to operate isothermally at the phase-change temperature.

Fig. 6 illustrates that one kilogramme of steam under vacuum condensating at 50 °C carries 2381 kilojoules of latent heat. This is considerably higher than the energy available from a kilogramme of liquid water as a heating medium, where each degree Celsius difference in process gas temperature represents 4.17 kilojoules of

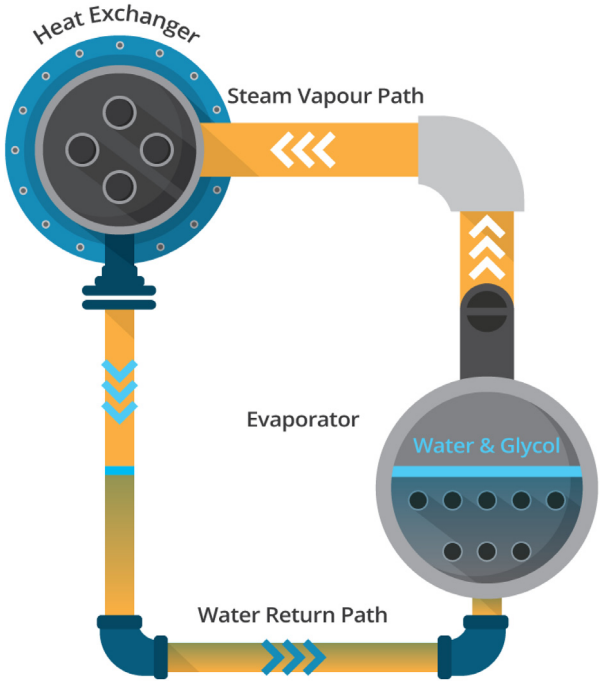

Fig. 5. Configuration of the immersion tube thermosyphon heater (ITTH).

transferable heat (Dickson and Fanelli, 2003). For example, where there is a difference of 30 °C between heating media and process gas temperatures, the maximum available energy per kilogramme of heating media is 125.1 kilojoules, 5.3% of the available energy for an equivalent mass of water vapour.

Operating under vacuum also resolves unwanted natural convection due to circulation of air in the system when the burner is turned off. If the system were to operate at atmospheric pressure, air and other non-condensable gases within the system would behave as a heat transfer medium, thus transporting heat from the evaporator to the condenser and potentially over-heating the natural gas once the burner is turned off. Eliminating this phenomenon allows the evaporator to remain at operating temperature (near vaporisation) and begin heat transfer more rapidly. The lack of air within the system also facilitates the transport of steam, as air and non-condensable gases act as an obstacle to heat transfer where vacuum is not established. Therefore, the ITTH operating under sub-atmospheric conditions has the benefit of near instantaneous and on-demand response.

Table 1
Summary of site specifications for the immersion tube thermosyphon heater (UK).

Heater type:	Immersion tube thermosyphon
Location:	United Kingdom
Inlet pressure:	65 bar (g)
Outlet pressure:	6.9 bar (g)
Nominal capacity:	104 000 SCM/h

The inherent heat transfer properties of a thermosyphon preheater, and the impact on thermal efficiency in an indirect heating application, are quantified and benchmarked against the two atmospheric water bath heaters in the following section.

2.2. Case studies

Three case studies are considered: one ITTH and two WBHs. For all three cases, the indirect heater installations are used to preheat natural gas at pressure reduction/city gate stations. Performance is compared in terms of efficiency, fuel use and associated CO_2 emissions. Note that the second and third case studies were completed prior to the first, so site specifications from literature are provided for comparative purposes.

Tabulated values shown for each case study highlight the load imposed on the given preheater. Inlet and outlet pressures are site average values representing the degree of gas pressure reduction, which in turn affects the temperature drop to overcome by the preheater, whilst nominal capacity specifies the amount of gas flow through each preheater.

2.2.1. Immersion tube Thermosyphon heater (UK)

Performance of a 1.8-megawatt Immersion Tube Thermosy phon Heater installation was evaluated during a winter heating season on a PRS in the United Kingdom, for which the heating requirements are summarised in Table 1. Note that process gas temperatures drop roughly 0.5 °C for every 1 bar of pressure reduction.

Site parameters – including operating pressure, outlet process gas temperature and gas/fuel flow rate – were recorded over 600 times every hour from an array of sensors, stored in the PLC

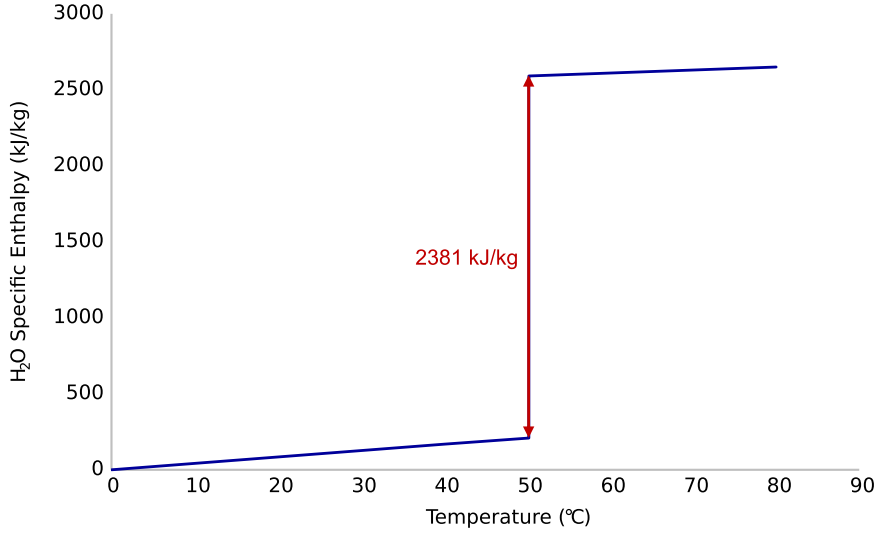

Fig. 6. Energy carrying capacity of water vaporising at 50 °C.

Table 2
Summary of site specifications for a water bath heater (UK).

Heater type:	Water bath
Location:	United Kingdom
Inlet pressure:	56 bar (g)
Outlet pressure:	7 bar (g)
Nominal capacity:	70 000 SCM/h

Table 3
Summary of site specification for a water bath heater (Iran).

Heater type:	Water bath
Location:	Shahrekord
Inlet pressure:	54 bar (g)
Outlet pressure:	2.5 bar (g)
Nominal capacity:	120 000 SCM/h

memory of the device and collected over a seven-day span. These are plotted against time and presented in the results section.

Note that, due to measurement discrepancies, preheater inlet gas temperature readings were not used in calculations. Gas was assumed to be at ground temperature, as it had travelled in below ground-level pipework for tens of kilometres before reaching the pressure reduction site. Monthly ground temperature readings collected between 1931 and 1960 are fitted using a sinusoidal curve to estimate an hourly temperature profile (Meteorological Office, 1968). As it is known that UK ground temperatures have risen due to global warming, an adjustment of +1.2 °C is applied based on a linear regression as detailed in Soil Temperatures (2017).

Thermal efficiency η_{th} of a heater is commonly defined as the ratio of useful energy transferred to heated gas versus total energy available in fuel consumed. For a heater, this value can show high sensitivity to the interval over which readings are processed. For instance, if the efficiency were calculated over a short time span, during which no fuel was consumed but stored heat was transferred to process gas, the heater would see an efficiency tending towards infinity. To remediate this issue, the efficiency was calculated over a seven-day period using Eq. (1), in which the hourly average useful energy transferred to the process gas $\overline{E_{PG,t}}$ was computed with Eq. (2).

$$\eta_{th} = \frac{\sum_{t=1h}^{T} \overline{E_{PG,t}}}{LHV \times m_{f,T}} \tag{1}$$

$$\overline{E_{PG,t}} = m_{PG,t} \times C_{p,PG} \cdot (\overline{T_{outlet,t}} - \overline{T_{inlet,t}}) \tag{2}$$

In Eq. (1), T represents the time span through which the readings were made and t is the time over which a parameter is averaged (seven days and one hour, respectively), while in Eq. (2), $\overline{T_{outlet,t}}$ and $\overline{T_{inlet,t}}$ are respectively the process gas outlet and inlet temperatures, averaged over the time span t. Furthermore, $m_{f,T}$ and $m_{PG,t}$ are respectively the mass of fuel consumed and heated process gas over their corresponding time spans, obtained from flow counter readings, with their respective densities assumed constant.

Eq. (1) shows that the useful energy transferred to process gas is averaged and calculated over the time span of the investigation. It is then divided by the total energy inputted into the system over that time – equivalent to the product of total fuel mass consumed and its lower heating value, which was assumed to be constant at 35 000 kJ/SCM – yielding a value for thermal efficiency.

The hourly average useful heat was calculated by computing the hourly average total enthalpy difference across the preheater as shown in Eq. (2), where $C_{p,PG}$ is the isobaric specific heat of the process gas assumed constant.

2.2.2. Water bath heater (UK)

A water bath heater installation located at a PRS site in the UK was evaluated by the authors, as part of a Strategic Pipeline Heat Study (Romocki et al., 2018). Operating parameters, including temperature, pressure and process gas flow, as well as fuel gas consumption, were monitored and processed as in the previous case. Site specifications are summarised in Table 2.

2.2.3. Water bath heater (Iran)

Khalili et al. (2012) carried out a 12-month evaluation to establish the seasonally-adjusted heater efficiency of a water bath heater located at the city gate station in Shahrekord; site specifications are shown in Table 3. Heat losses including combustion losses and losses to ambient were evaluated.

Note that, although the site specifications vary for the different case studies, heater thermal efficiency can be assumed independent of nominal capacity, as it is an indicator of the unit's capacity to transform potential chemical energy in fuel into useful heat, regardless of heat load. In the Discussion chapter, potential fuel savings related to differences in thermal efficiency are compared for the three cases. This value is site-dependent and, therefore, sites were normalised based on 1-megawatt gross heat capacity operating with a 50% load factor.

3. Results

This section summarises findings made in the ITTH case study, which are discussed and compared to findings from two WBH case studies.

3.1. Preheat load diversity

Fig. 7 illustrates the high load diversity imposed over the seven-day period in which the ITTH was investigated. The preheater inlet pressure varies unpredictably with time and, since the outstation pressure must be kept quasi-constant, the difference in pressure and resulting temperature difference to overcome is variable. The erratic variations in station inlet pressure occur due to balancing requirements for supplying gas demand within the network: when more gas than required is inputted into the system, it is stored in the high-pressure network resulting in a higher PRS inlet pressure. The process gas flow fluctuations have a distinguishable pattern, which is to be expected as the two daily spikes in gas flows correspond to morning and evening peak gas demand.

3.2. Useful heat

Fig. 8 depicts the variation of the heater process gas outlet temperatures (before expansion). This data, along with the inlet temperature, are used to calculate an hourly average entropy difference across the preheater and, therefore, the useful energy transferred to the process gas using Eq. (2). Note that the preheater control feedback calculates the temperature error from a probe placed at the station outlet. Temperature control performance is discussed in the following subsection.

3.3. Temperature control

Fig. 9 shows outstation temperatures over a seven-day period. The same vertical axis sensibility as that in Fig. 3 is selected to facilitate ease of comparison between the ITTH and a standard WBH performance. Note that 95% of values fall within 0.5 °C of the 2 °C station temperature set point, showing a clear improvement in control relative to the WBH. Overheating losses, defined as the losses relating to fuel use beyond that which is required to maintain safe operating temperature after a pressure reduction, have not been quantified. However, a comparison of total useful fuel use will be the focus of further investigation.

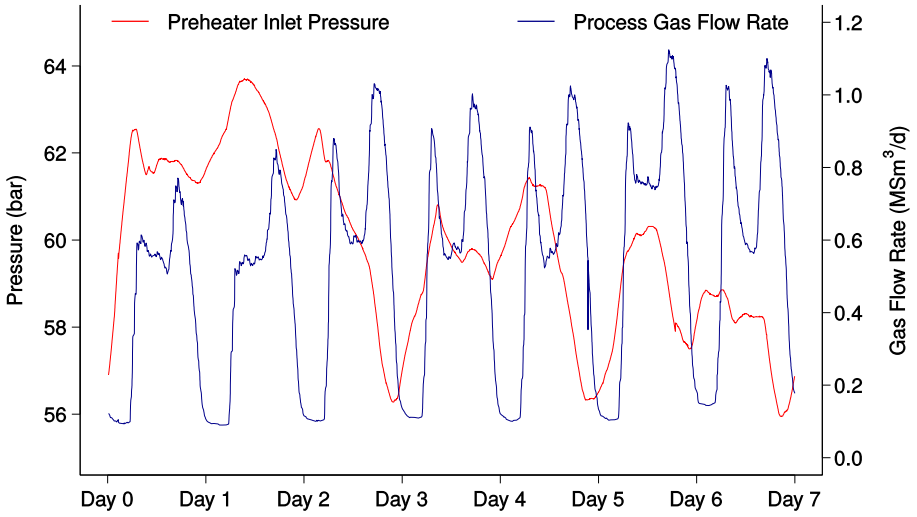

Fig. 7. Preheater inlet pressure and gas flows over a seven-day period.

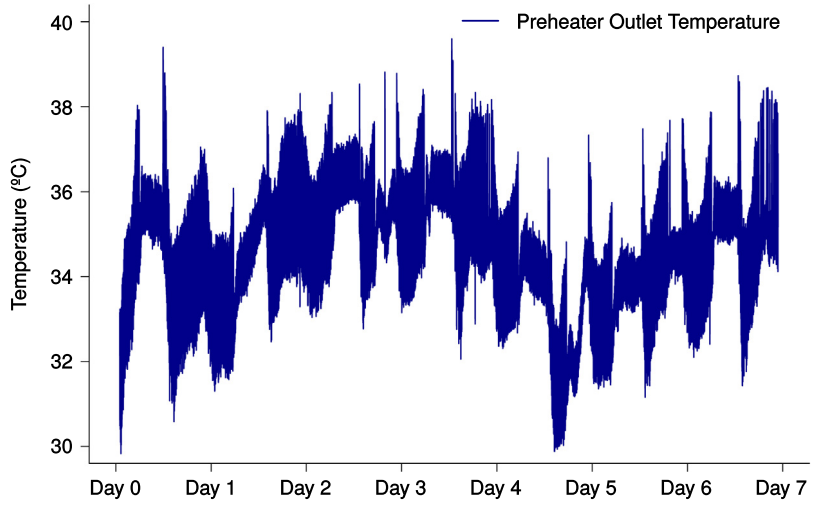

Fig. 8. Preheater outlet temperature over a seven-day period (prior to pressure reduction).

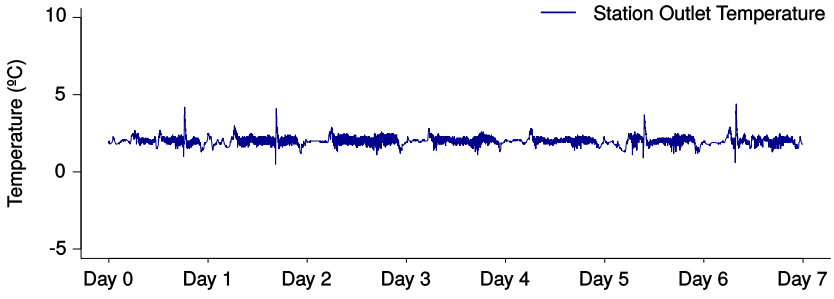

Fig. 9. PRS outlet temperature over a seven-day period (after pressure reduction).

Table 4
Efficiency summary of preheat installations.

Case	Indirect heater type	Nominal capacity (SCM/h)	Thermal efficiency (%)
1	Immersion tube thermosyphon	104 000	90
2	Water bath	70 000	46
3	Water bath	120 000	47

Table 5
Fuel gas saving compared to base case (GSCC) and CO_2 saving comparing to base case (CSCC).

Case	Indirect heater type	GSCC (SCM/year)	CSCC (Tonne/year)	Avoided fuel (£/year)
1	Immersion tube thermosyphon	419 000	7660	£62 800
2	Water bath	0	0	0
3	Water bath	18 000	333	£2700

3.4. Heater thermal efficiency

Using Eqs. (1) and (2), the data shown in this section yields a thermal efficiency of 90% for the ITTH. This value is compared to results from the WBH cases in the Discussion chapter below.

4. Discussion

A summary of the nominal site flows and thermal efficiencies are provided in Table 4.

As compared to the two WBH cases, the ITTH offers a significant improvement in thermal efficiency. This is a result of the evaporator's ability to extract a much greater proportion of the heat from burner flue gases and to efficiently transfer energy within the two-phase loop thermosyphon. Furthermore, the two WBHs yield similar thermal efficiencies even though they operate on sites with very different nominal capacities, indicating that heater thermal efficiency does not necessarily depend on heat loads.

There was a clear improvement in response time and control accuracy displayed by the ITTH, resulting in additional fuel savings from reduced overheating and the potential for a lower station temperature set point. The reduction in temperature deviations from the set point is supported by comparing Figs. 3 and 9. Improvements in control can be attributed to the increased rates of heat transfer occurring within a dual-phase heat exchanger (steam and water). Phase change of heat transfer media in the condensing zone of the ITTH results in a greater heat transfer coefficient relative to that achieved by single-phase indirect heaters, which rely exclusively on temperature difference between heating media and process gas. Additionally, the ITTH requires 80%–85% less liquid to achieve an equivalent power rating as a WBH, thus providing an improved power-to-mass ratio, leading to quicker, more easily controlled thermal response.

To quantify fuel savings and associated reductions in CO_2 emissions across the three indirect heating installations, Case 2, representing the lowest efficiency, is used as a base case. For ease of comparison, all units are normalised to have a 1-megawatt gross heat capacity running at a 50% load factor, or an average load of 500 kilowatts. Using a value for natural gas of 0.15 GBP/m^3 (Energy Solutions, 2017), annual fuel savings are considerable.Table 5 summarises fuel gas and CO_2 savings relative to the base case and provides an estimate of the financial savings from improved efficiency.

The comparison illustrates 419 000 SCM of anticipated fuel savings associated with the ITTH installation, providing a saving of £62 800 per year relative to the base case. The associated reduction in CO_2 emissions is equivalent to 7660 tonnes per year.

Note that fuel savings resulting from improved control were beyond the scope of this study, in which all heat transferred to process gas was assumed useful. Further research will consider potential savings in fuel gas associated with improved control and reduced deviations from an ideal set point value.

5. Conclusion

Within the structure of a sustainable energy system, asset performance has become a focal point for gas distribution networks. This investigation used experimental data to compare thermal performance of the Immersion Tube Thermosyphon Heater (ITTH) with that of conventional single-phase preheat technology. The ITTH was able to increase thermal efficiency, reduce carbon emissions and improve temperature control without compromising system reliability. A key benefit of the design – though not quantified in the scope of this paper – is the ability to respond quickly to transient heat requirements, offering a level of flexibility and control previously unachievable with single phase heating technology. The Immersion Tube Thermosyphon achieved an average efficiency of 90%, considerably higher than the 46% efficient water bath, allowing an estimated annual saving of 7660 tonnes CO_2 for 1-megawatt gross heat capacity operating with a 50% load factor.

Declaration of interest

The authors of this document are the manufacturers of the Immersion Tube Thermosyphon Heater, part of the apparatus used in this investigation. Performance data from the Immersion Tube Thermosyphon Heater was gathered as part of the OFGEM funded Low Carbon Gas Preheating (LCGP) project. This research paper did not receive any specific grant from funding agencies in the public, commercial or not-for-profit sectors.

References

Bieliński, H., 2016. Validation of the generalized model of two-phase thermosyphon loop based on experimental measurements of volumetric flow rate. Arch. Thermodyn. 37 (3), 109–138. http://dx.doi.org/10.1515/aoter-2016-0023.

Dickson, M.H., Fanelli, M., 2003. Geothermal Energy : Utilization and Technology. Earthscan.

Energy Solutions, 2017. Historical Wholesale UK Natural Gas Prices. Retrieved August 15, 2017, from http://www.energybrokers.co.uk/gas/historic-price-data-graph.htm.

Franco, A., Filippeschi, S., 2012. Closed loop two-phase thermosyphon of small dimensions: A review of the experimental results. Microgravity Sci. Technol. 24 (3), 165–179. http://dx.doi.org/10.1007/s12217-011-9281-6.

Khalili, E., Mostafa Hoseinalipour, S., Heybatian, E., 2012. Efficiency and heat losses of indirect water bath heater installed in natural gas pressure reduction station evaluating a case study in Iran. National Iranian Gas Company.

Lamaison, N., Ong, C.L., Marcinichen, J.B., Thome, J.R., 2017. Two-phase mini-thermosyphon electronics cooling: Dynamic modeling, experimental validation and application to 2U servers. Appl. Therm. Eng. 110 (110), 481–494. http://dx.doi.org/10.1016/j.applthermaleng.2016.08.198.

Matallah, H., Newton, W., James, D., Cameron, I., Sienz, J., Romocki, S., Lavery, N.P., 2016. The development of a sub-atmospheric two-phase thermosyphon natural gas preheater using a lumped capacitance model and comparison with experimental results. Appl. Therm. Eng. 104, 767–778. http://dx.doi.org/10.1016/j.applthermaleng.2016.05.078.

Meteorological Office, 1968. Average of Earth Temperature at Depths of 30 cm and 122 cm for the United Kingdom. Her Majesty's Stationary Office.

Romocki, S., Zarkesh, J., Cheung, I., 2018. ENA Smarter Networks Portal. Submitted for Publication. Retrieved from http://www.smarternetworks.org/Project.aspx?ProjectID=2058.

Sabharwall, P., Patterson, M., Gunnerson, F., 2008. Theoretical design of thermosyphon for process heat transfer from ngnp to hydrogen plant. In: Fourth International Topical Meeting on High Temperature Reactor Technology, Vol. 1, ASME, pp. 733–738. http://dx.doi.org/10.1115/HTR2008-58199.

Soil Temperatures, 2017. Retrieved June 22, 2017, from http://www.halesowenweather.co.uk/soil_temperatures.htm.

Wagner, A., 2014. Review of Thermosyphon Applications. The US Army Engineer Research and Development Center (ERDC), (ERDC/CRREL TR-14-1).