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Experimental heat exchanger test facility for evaporation and condensation of hydrocarbons

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ABSTRACT

Utilisation of natural working fluids based on hydrocarbons can reduce greenhouse gas emissions considerably. However, components and systems need to be developed further to fully exploit their thermo-physical properties. A new heat exchanger test rig is under construction at SINTEF Energy Research's thermal laboratories in Trondheim. The rig is designed to test novel heat exchanger concepts and designs for hydrocarbons and mixtures of these. Heating, cooling, evaporation, and condensation experiments can be performed at temperatures ranging from 0 – 150 ˚C and pressures up to 70 bar(g), for heat exchangers with thermal capacities up to around 20 kW. This paper describes the design, test capabilities and accuracy of the experimental setup.

Keywords: Heat transfer, pressure drop, experimental, hydrocarbons, mixtures, heat exchanger prototypes, evaporation, condensation, temperature glide

1. INTRODUCTION

International legislations such as the Montreal protocol compel the industry to phase out working fluids that can damage the ozone layer and the climate [1]. An alternative to such fluids are hydrocarbons, which can operate both efficiently and environmentally friendly in different energy systems [2-4]. Furthermore, the performance of hydrocarbon working fluids can be improved by mixing different hydrocarbons, owing to the temperature glide created during heat transfer as well as the adaptation of thermodynamic properties [5, 6]. With the rise of hydrocarbons and their mixtures as preferred working fluids, there is a need for new heat exchangers that are specifically optimized for these fluids [7]. Our work describes an experimental heat exchanger test facility that will be used to test the performance of new heat exchanger concepts for hydrocarbon heat transfer, including heating, cooling, evaporation, and condensation. The rig will also be used to investigate optimal hydrocarbon mixtures under different conditions.

Compact heat exchangers and enhanced heat exchanger geometries are considered promising for hydrocarbons, as they reduce the charge of the flammable working fluid circulating in the system [7]. An example of such a heat exchanger is the plate heat exchanger, which is both energy efficient and compact [8, 9]. Plate heat exchangers will be part of the first test campaign in the lab facility. In fact, experimental data on evaporation and condensation of hydrocarbons in plate heat exchangers is rather sparse [9], and our test rig will therefore enable important contributions to this research field. Future test campaigns will likely also involve testing of other heat exchanger types, and hydrocarbon mixtures, for which experimental studies are considered "extremely rare" [5].

Results from the experimental tests will be used to determine which heat transfer and pressure drop correlations that correspond best with the experimental data. Correlations for predicting heat transfer and pressure drop can yield very diverging results due to the different conditions involved during development of the correlations [5, 10]. As a result, the different correlations will result in different optimal heat exchanger design, and we cannot know which design is the real optimum. Thus, identifying the most suited correlations will be useful for future conceptual design and optimization.

1.1. Example of the impact of correlation choice on heat exchanger design

An example of the consequence of correlation choice on plate heat exchanger design is given in this section. In the demonstration case, a cascade plate heat exchanger with boiling hydrocarbon on the cold side and

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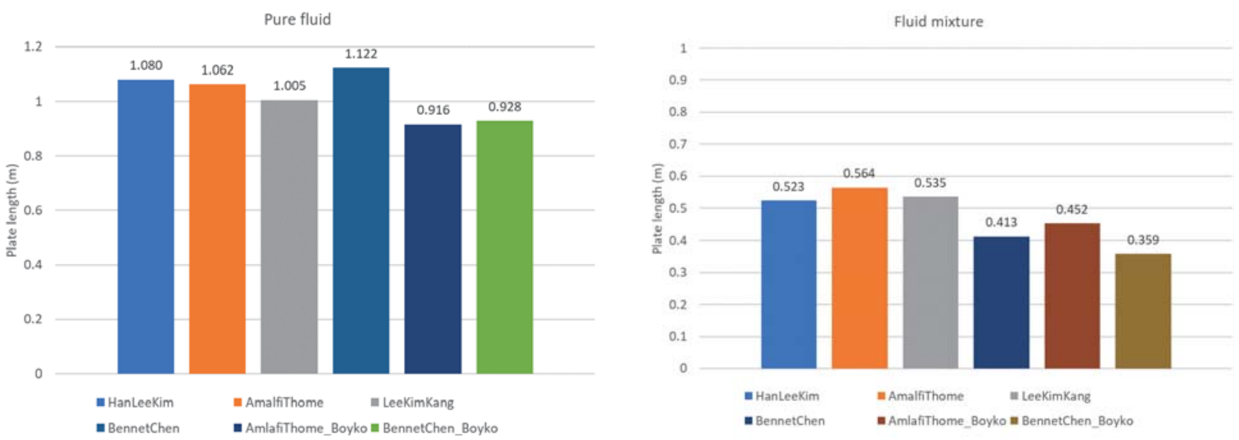
condensing hydrocarbon on the warm side is used. Two examples are provided, one with pure hydrocarbons and one using a hydrocarbon mixture. For both cases, a plate heat exchanger that will provide 300 kW capacity is designed, using plates with a 60° chevron angle, 2.0 mm mean plate gap and a plate width of 240 mm. The number of plates is set to 150 for the pure hydrocarbon case, and 50 for the hydrocarbon mixtures. For the case with pure hydrocarbons, propane is used on the warm side and butane on the cold side of the heat exchanger. The mixtures are 80/20 molar % propane/butane on the condensing side and 20/80 molar % propane/butane on the boiling side. The condensing and boiling pressures are set to 17.5 bar and 4.65 bar, respectively, for both cases. With our case specifications, the use of mixtures will give a much higher temperature difference between the warm and cold stream – thus the lower number of plates. The plate heat exchanger model solves the length for the specified duty (300 kW) and the plate lengths are compared when different underlying models are used. The plate heat exchanger models are created with a flexible in-house modelling framework [11] and the thermodynamic properties are calculated with a corresponding state method [12] using the Peng-Robinson Equation of State (EOS) for scaling and with propane as a reference fluid and reference equation Lemmon, McLinden [13]. The test correlations are shown in Table 1.

Table 1: Overview of the tested heat transfer and pressure loss correlations

	Single-phase	Two-phase		
Case		Evaporation	Condensation	Pressure loss
1	Martin [14]	Han-Lee-Kim [15]	Han-Lee-Kim	Han-Lee-Kim
2		Amalfi-Thome [16]	Han-Lee-Kim	Amalfi-Thome
3		Lee-Kang-Kim [17]	Han-Lee-Kim	Han-Lee-Kim
4		Bennet-Chen [18]	Han-Lee-Kim	Han-Lee-Kim
5		Amalfi-Thome	Boyko-Kruhzilin [19, 20]	Amalfi-Thome
6		Bennet-Chen	Boyko-Kruhzilin	Amalfi-Thome

The plate-specific correlation from [15-17] are compared to the general flow boiling correlation by Bennet-Chen [18]. According to Djordjevic and Kabelac [21] the use of a general tube boiling correlation combined with an accurate single phase heat transfer and frictional pressure loss correlation [14] could provide a reasonable result. They suggested a 'tube-to-plate' scaling factor depending on the chevron angle (0.82 for 27° and 0.51 for 60°), which is used here. The results from the calculations are shown in Figure 1. The large difference in the calculated plate length between the pure hydrocarbon case to the left and the mixture to the right is because the mean temperature difference is larger in the case of mixtures. The first three correlations for both cases are plate specific and the variation in calculated length seem to be relatively moderate, varying between 1005 and 1080 mm for the pure fluid case and between 523 and 564 mm for the mixture case. When the Bennet-Chen correlation – scaled to plate geometry is used, the pure component case indicates poorer heat transfer capabilities and a plate length of 1122 mm is required for 300 kW duty. For the mixture case, the situation is the opposite, where the use of the scaled tube flow correlation indicates better heat transfer capabilities and a plate length of only 413 mm is sufficient. The condensation heat transfer correlation by Boyko and Kruzhilin (with modifications by Chisholm) also gives a generally higher heat transfer rate and thus shorter plate lengths.



Number of plates: 150. Propane (cond), Butane (boil)   *Number of plates: 50 Propane/Butane (80/20 cond, 20/80 boil)*

Figure 1: Plate lengths for a cascade plate heat exchanger based on different two-phase heat transfer correlations

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The difference in heat exchanger design depending on the choice of correlations shown in these examples illustrates why experimental testing will be important in the design and development of future heat exchangers for hydrocarbons.

2. EXPERIMENTAL FACILITY

The heat exchanger test facility will allow testing of new heat exchanger concepts, prototypes, and hydrocarbon working fluids. The facility is currently under construction in SINTEF Energy's laboratories in Trondheim, Norway and will be operational in Q4 2020. The infrastructure will enable development of new heat exchanger concepts for next-generation waste heat recovery, heat exchange, heat pumps and heat-to-power processes. The infrastructure will be used for both basic research (model development) and commissioned research (prototype testing, validation). A description of the test rig and test capabilities are given in the following.

2.1. Experimental setup

A simplified schematic of the research infrastructure is shown in Figure 2. The rig is divided into four circuits shown in black, blue, red and green. Additionally, the rig is connected to the laboratory's cooling water and CO_2 cooling circuits. Red stippled lines show which sensors are used to control heaters and control valves. All circuits are insulated. Some of the main specifications for the test rig are summarised in Table 2.

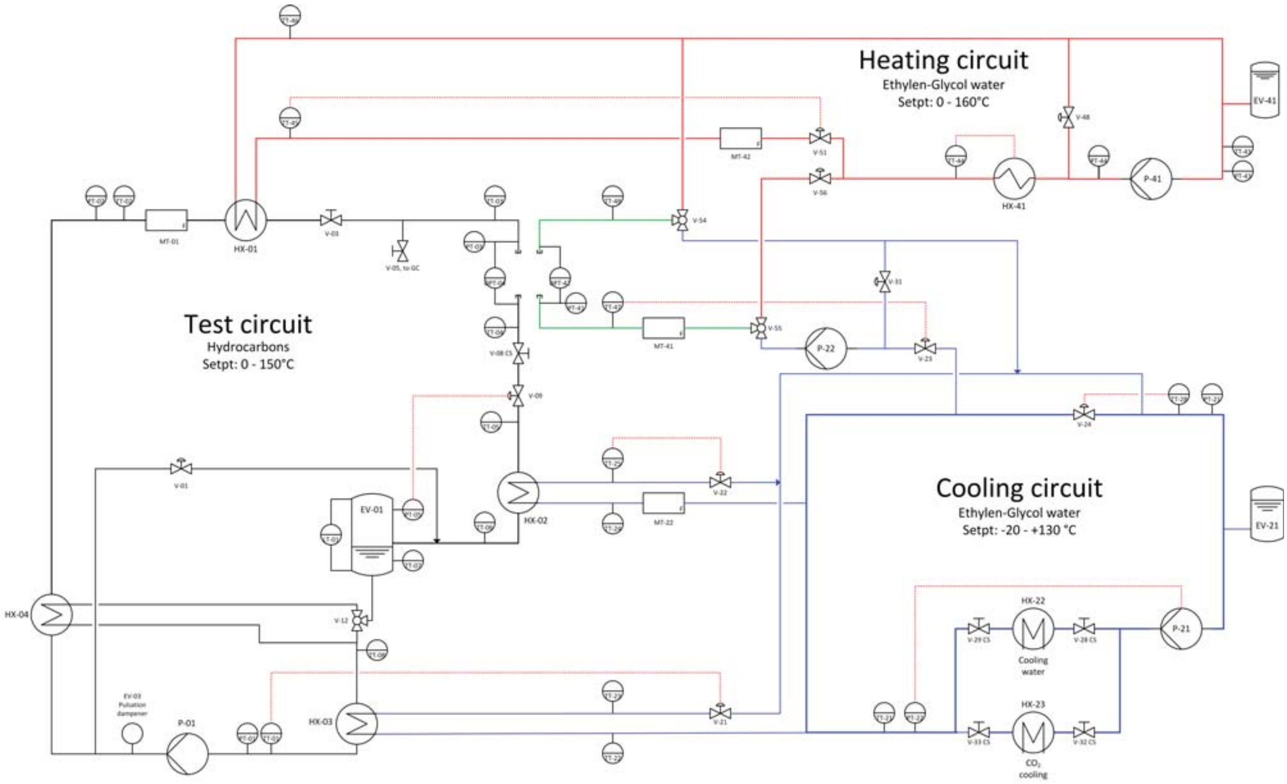

Figure 2: Simplified schematic of the experimental setup

Table 2: Main specifications for the heat exchanger test rig

Specification	Black circuit at test section	Blue circuit	Red circuit
Fluids	(Ethane in mixture), propane, butane, pentane	Ethylene-glycol water	Ethylene-glycol water
Mass flow	Up to 20 kg/min	Up to 50 lpm (test section) and 85 lpm (main)	Up to 80 lpm
Temperature	0 – 150 ˚C	-20 to +130 ˚C	0 – 160 ˚C
Pressure	Up to 70 bar(g)	Up to 12 bar(g)	Up to 12 bar(g)

2.1.1. Black test circuit

The circuit shown in black is the test circuit. Starting from expansion vessel EV-01, the liquid working fluid can either be cooled in recuperator HX-04 before entering the sub-cooler HX-03, or HX-04 can be bypassed

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depending on the positioning of three-way valve V-12. The sub-cooled liquid is then pumped to the desired test pressure using a membrane pump followed by a pulsation dampener, yielding a virtually pulsation free flow. A recirculation loop from the pump outlet back to the expansion vessel inlet can be used if mass flow rates lower than the minimum capacity of the pump is desired. The pressurised liquid passes through the recuperator, HX-04, before it enters heat exchanger HX-01, where the working fluid is heated, evaporated, or partly evaporated to achieve the desired inlet conditions for the test section. In the test section, described in more detail in a later section, the working fluid can be heated, evaporated, cooled or condensed in a test heat exchanger. After the test section, the working fluid is throttled down to a lower pressure in control valve V-09 and condensed in HX-02. The stream enters expansion vessel EV-01, where a liquid level is kept.

2.1.2. Blue cooling circuit

The blue circuit provides the cooling duty for the black circuit. Starting from the circulation pump, P-21, ethylene – glycol water can be cooled either by cooling water in heat exchanger HX-22 or by CO_2 in HX-23 depending on the desired temperature level. Branches from the main cooling circuit to the sub-cooler, HX-03, condenser, HX-02, and test heat exchanger provides cooling to each of these. The branch for the test heat exchanger is solely used for cooling and condensing experiments. Control valves V-21 and V-22 controls the cooling duty for the sub-cooler and condenser, respectively. Each branch is instrumented with temperature sensors. The branch for the condenser is also equipped with a Coriolis mass flow meter. The branch for the test section in equipped with an own pump and recirculation loop, to be able to control the temperature on the cold side of the test heat exchanger. The circuit entering the test section, in green, is connected to the blue cooling circuit via three-way valves, V-54 and V-55. These can be positioned such that either cooling duty from the blue circuit or heating duty from the red circuit can be provided to the test heat exchanger.

2.1.3. Red heating circuit

The red circuit provides the heating duty for the pre-heater/evaporator and the test heat exchanger for heating and evaporation experiments. Starting from circulation pump P-41, ethylene – glycol water is heated to the desired temperature in an electrical heater, HX-41. The stream splits into two branches. One branch can enter the test section if the three-way valves are positioned for heating/evaporation experiments. The other branch provides heat for heat exchanger HX-01. This branch is instrumented with a mass flow meter and PT100 temperature elements on the inlet and outlet of HX-01.

2.1.4. Green circuit – test section

The test section is illustrated in Figure 3. On the test fluid side, pressurised liquid enters Coriolis mass flow meter MT-01, and the pressure and temperature are measured with a high accuracy pressure sensor and PT100 element. The fluid is then heated in HX-01 to achieve the desired inlet conditions for the test section. The warm side of HX-01 is instrumented with a Coriolis mass flow meter and high accuracy PT100 elements on the inlet and outlet of the heat exchanger. The mass flow of the heat source is controlled using V-51. Hence, the heat input to the test fluid in HX-01 can be accurately controlled, and it is thus possible to enter the test heat exchanger with a specified vapor fraction. After HX-01, there is a sampling point for measurement of composition that can be used in experiments where mixtures are used as working fluid. PT100 elements are installed at the inlet and outlet of the test heat exchanger. The absolute pressure is measured at the inlet, and a differential pressure transmitter measures the pressure drop across the heat exchanger. Control valve V-09 is used to throttle the fluid down to the condensing pressure.

On the heat source/sink side, the three-way valves V-54 and V-55 are used to determine if the test section is connected to the red heating circuit or the blue cooling circuit. The ethylene-glycol water flows through Coriolis mass flow meter MT-41 before entering the test heat exchanger. PT100 elements are installed on the inlet and outlet of the test heat exchanger. The absolute pressure is measured at the inlet, and a differential pressure transmitter measures the pressure drop on the ethylene-water side of the test heat exchanger. The rig is designed such that the test section can be easily changed and facilitates for additional temperature and pressure sensors that can be installed in the test heat exchanger if required. The test rig is designed to be flexible and can handle both plate and tube type heat exchangers, as well as new concepts.

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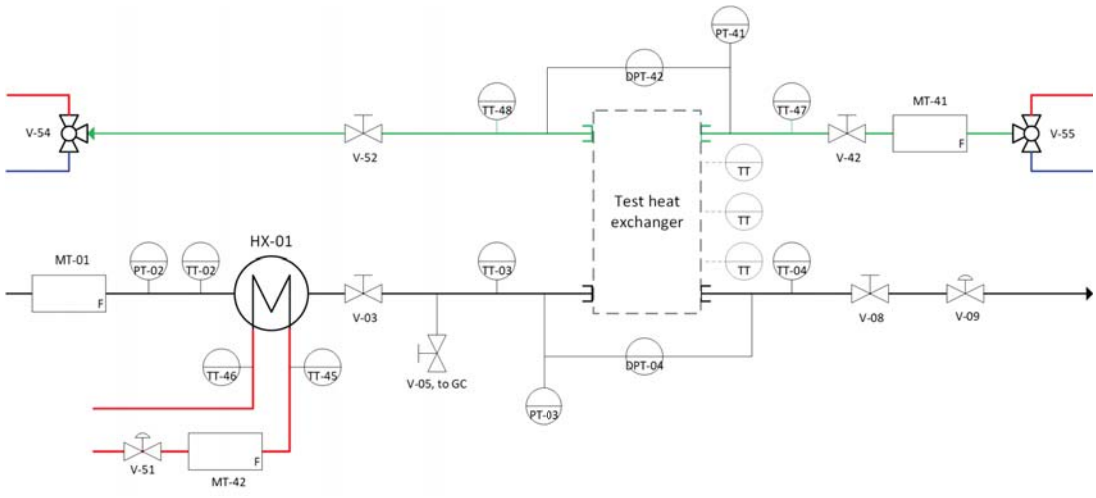

Figure 3: Simplified schematic of the test section

2.2. Uncertainty analysis

The design goal for the experimental uncertainty have been 0.5 % in the duty for the test section. The combined uncertainty in the measured quantities X_i used to calculate the total heat transfer is estimated as

$$u_c^2(y) = \sum_{i=1}^{n} \left(\frac{\partial f}{\partial x_i}\right)^2 u^2(x_i)$$

For a formal calculation, these uncertainties should be calculated with the partial derivatives from the EOS. In the design we have only considered a simplified calculation without the uncertainty in the EOS. For a case with a subcooled liquid at the inlet and superheated vapour at the outlet the total duty could be estimated as:

$$Q_{tot} = \dot{m}\left(c_{p_{satliq}}(T_{sat}(p) - T_{in}) + \Delta h_{vap} + c_{p_{satvap}}\big(T_{inout} - T_{sat}(p)\big)\right)$$

We have calculated the expanded total uncertainty for a case with an evaporation of Butane. The inlet temperature is 299 K, the saturation temperature is 300 K and the outlet temperature is 301 K. The duty for the calculation is 20 kW. With these conditions the uncertainty in the measured heat transfer is 0.18 % (k=1). excluding the uncertainty in the EOS. A similar exercise is done for the heat source with a temperature difference in the heat transfer fluid (water) at 8 K. The uncertainty for the green circuit is then 0.88 %. The uncertainty of the measured pressure drop is 0.04 % of reading for a pressure difference larger than 60 mbar. The total uncertainty in pressure difference should also be corrected for eventual difference in fluid column between inlet and outlet and the uncertainty in density for these columns.

3. CONCLUSIONS

Hydrocarbons and their mixtures are becoming preferred working fluids for several applications due to their favourable thermo-physical properties and low environmental impact. There is however a need to develop new compact heat exchangers that are specifically optimized for these fluids. This paper describes the design, test capabilities and accuracy of a new heat exchanger test rig for hydrocarbons and mixtures that is under construction in SINTEF's laboratories in Trondheim. The rig has a design that allows for testing of evaporation and condensation in different types of heat exchangers at temperatures ranging from 0 – 150 ˚C and pressures up to 70 bar(g), for heat exchangers with thermal capacities up to around 20 kW. There is currently little experimental data available for evaporation and condensation of hydrocarbons in compact heat exchangers, and existing correlations for predicting heat transfer, pressure drop and corrections for the use of working fluid mixtures can yield very diverging results due to the different conditions involved during development of the correlations. There is therefore a need to test and identify the most suited existing correlations and develop new correlations if required, for development of future compact heat exchangers. The test rig will enable important contributions to this research field. The uncertainty in the example case used in the uncertainty analysis shows that heat exchanger tests with high accuracy can be performed in the rig, with an uncertainty of 0.18 % in transferred heat and 0.04 % in pressure drop for the example case.

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