Design of a Test Rig for the Simulation of Startup Procedures in Main Heat Exchangers of Air Separation Plants

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The Kopernikus project "FlexASU" investigates an enhancement of the load flexibility of air separation units with the goal to synchronize their power consumption with the availability of renewable energy sources. The main heat exchanger of these plants was identified as a key component for a dynamic plant operation because startup, shutdown and load change procedures can lead to thermal stress and an increased lifetime consumption of the apparatus. Aluminium brazed plate fin heat exchangers (PFHE) are used in these plants because of their high process integration, low production cost and compact design. Finding the optimum operating scheme for the rectification columns depends on detailed knowledge of their effect on the lifetime of the PFHE.The transient behavior of temperature profiles within a PFHE can be calculated and a FEM-based model is available to investigate the thermal stress induced by dynamic temperature changes in the apparatus. Hence, the reduction of lifetime due to certain dynamic plant operating scenarios can be estimated and critical operating modes can be identified. For further development of the model, a PFHE test rig is designed which is representative for extreme operating conditions in air separation units. A test scenario matching the conditions of plant startup after extended downtime in cold condition has been designed. To reach a level of thermal stress comparable to industrial sized plants, the PFHE weighing around 1.5 tons is heated up to 50 °C before rapidly being cooled down by a stream of gaseous nitrogen at -173 °C in a cyclic operation scheme. This test scenario leads to thermal stress that is expected to damage the PFHE within a few weeks of testing and the location of maximum thermal stress in the FEM model matches typical cracks observed in PFHE of air separation units. The test rig is designed to gain a clearer understanding of the underlying damage mechanism and to evaluate measures for lowering thermal stress in further test series. The knowledge gained from the experimental investigations is crucial for maximizing the operation flexibility of an ASU plant.

1. Introduction

The Kopernikus projects were introduced by the Federal Ministry of Education and Research due to the German energy policy. As part of the "Energiewende", Germany wants to increase the share of renewable energies in its power supply. Until 2050, 80 % of the gross electricity consumption should come from renewables (BMBF, 2017a). The goal of the Kopernikus projects is therefore to develop new energy concepts which can be used in industry on a large technical scale. The project "SynErgie" focuses on flexible operations of energy intensive processes in industry. Air separation units (ASUs) have a high potential of helping to stabilize the power grid due to their high energy demand, widespread application and high-density storage capacity. The flexible operation of these plants is investigated in the sub-project "FlexASU". The target is to synchronize the energy demand of ASUs with the volatile availability of renewable energy sources (BMBF, 2017b). This requires highly dynamic operation of ASUs as the amount of power supplied by renewables can shift within hours. While rectification columns are usually in the focus of a cryogenic ASU, the high process integration, which is necessary for a good efficiency, leads to the fact that the employed main heat exchanger is a key unit for the dynamic behavior of the plant. Flexible operation of an ASU results in a high frequency of

load changes for the aluminum brazed plate fin heat exchanger (PFHE). Transient operating conditions like startup and shutdown can lead to thermal stress and ultimately cause material fatigue and damage in PFHEs. The flexibility of an ASU is therefore not only limited by the rectification process but also by the capability of the PFHE to withstand the stress that can be caused by rapid change in process flow rates and temperatures. To determine the optimum operating scheme of the rectification columns, it is necessary to understand the behavior of the PFHE.Thus, a method to evaluate the thermal stress caused by dynamic operation conditions of PFHE has been developed (Hölzl 2012). The model has already been applied to experimental thermal fatigue tests of relatively small PFHE test units by Hölzl and Flüggen (2013). However, it is difficult to validate against large heat exchangers because to date, ASU plants are rarely operated with high load flexibility, so damage caused by thermal stress is a very rare phenomenon. Furthermore, Linde offers product lifetime estimation studies as a service that evaluates the impact of thermal stress events of PFHE running in existing plants.The goal of this project is to use the available model along with experience gathered from experimental thermal fatigue tests and in field applications of PFHE in order to design a test rig which can be used for further enhancement and validation of the computational lifetime estimation of large PFHE in transient operating conditions. The test rig will later also be used to evaluate improved manufacturing methods and operating schemes which enable more flexible operation of ASUs by avoiding thermal stress and related damages. Thus, the experimental setup needs to be able to simulate the desired dynamic operating conditions of a flexible ASU.

2. Model based estimation of thermal stress

The model environment used to investigate thermal stress in PFHE caused by dynamic operation within this project consists of two subsequent calculation steps that are explained briefly in this section. A more detailed description of the employed models is given by Woitalka et al. (2015) and Hölzl (2012).

2.1 Thermohydraulic simulation

In the first step, the desired transient operating scenario, e.g. startup, cold restart, shutdown or load change, is investigated using Linde Engineering's in-house process simulator OPTISIM. The tool uses a rapid solver for systems of partial differential equations (PDEs) to solve the relevant dynamic energy balances in a heat exchanger. This results in knowledge of the transient temperature and pressure distribution within the apparatus. A simplified example of the energy balance for a process stream in a PFHE is given in Eq(1) with the stream's temperature T, thermal conductivity λ, density ρ, specific isobaric heat capacity c_P, flow velocity u, heat transfer coefficient α, volume specific area of heat transfer a_V, temperature of the surrounding metal T_M, time t and one spatial dimension x:

$$\frac{\partial T}{\partial t} = \frac{\lambda}{\rho \cdot c_P} \cdot \frac{\partial^2 T}{\partial x^2} - u \cdot \frac{\partial T}{\partial x} - \frac{\alpha \cdot a_V \cdot (T - T_M)}{\rho \cdot c_P}. \tag{1}$$

According to Eq(1) the transient energy balance depends on thermal conductivity, convective heat transfer and convection itself. Using OPTISIM, these equations can be solved considering temperature and pressure dependent material properties and the exact fin geometry of the PFHE. Material properties are calculated using Linde's proprietary database GMPS. Detailed correlations for the pressure drop and heat transfer coefficient are available even for two-phase streams and conditions like condensation and evaporation.

The effects of transient behavior of auxiliary equipment like the expansion turbines of an air separation unit on the PFHE can also be considered because OPTISIM offers appropriate models for these units. This enables detailed calculation of the stream and metal temperature profiles in a multi-stream PFHE under a big variety of operating conditions. The results of this thermohydraulic simulation are used as a basis for the estimation of thermal stress.

2.2 Finite Elements analysis

After calculation of the stream temperature distribution, the thermal stress of the operating scenario is evaluated using commercial software for FE analysis. In this step, a 3D model of the PFHE capturing its major geometric features to reproduce the desired boundary conditions is used. This includes the layer distribution, sidebars, headers, cap sheets and dummy layers. The fluid temperatures and heat transfer coefficients calculated during the thermohydraulic simulation are applied to the respective passages of the PFHE. Using this information, a detailed transient temperature distribution of the solid part of the heat exchanger can be calculated. The resulting temperature gradients in the PFHE lead to varying thermal expansion. Stresses can then occur due to the applied boundary conditions and restrictions in expansion of the PFHE. Certain scenarios like plant startup or shutdown lead to thermal stresses in different quantity. Every occurred event reduces the remaining lifetime of the PFHE and can therefore be summed up in order to give an estimation

about the actual lifetime consumption using the Miner's rule. This can be used both in the design and operating phase of a plant and has already been used for fatigue evaluation of smaller test rigs by Hölzl and Flüggen (2013) and applied to heat exchangers in the field by Freko et al. (2015).

3. Test rig for PFHE lifetime estimation

The main target of this work is to design a test rig that can be used as a representative of large-scale ASU main heat exchangers with respect to typical failure modes and probability of failures. The challenge is to design a PFHE which is representative but still small enough to be put into a reasonably sized test rig. This demonstration unit will then be exposed to a continuously reoccurring test scenario for dynamic plant operation until it is damaged by material fatigue. The location and number of thermal stress events for the first damage of the test scenario will then be compared to the model results. The PFHE should undergo a cyclic series of cooldown and warmup procedures. Thus, it is planned to design and build a setup in which two identical heat exchangers are employed in parallel with anticyclical operation. This not only helps saving utilities but also with the fact that material fatigue is a statistical problem that can be handled better with more than one test unit. The definition of the test scenario, the design of the PFHE test units and the basic engineering of the auxiliary equipment for the test rig are presented one by one within this section. This in fact adds up to one highly linked integrated task because manufacturing restrictions already have to be considered during the design of the test case.

3.1 Definition of a dynamic test scenario

The key challenge of defining a representative test scenario for transient operating conditions of an air separation unit is that there are numerous possible ways to achieve startup, shutdown or load changes in a real plant with a multi-stream PFHE. Because the amount of thermal stress induced by these scenarios varies vastly, this work is focused on quick startup scenarios which are known for leading to high thermal stress because of rapid temperature changes in the heat exchanger.

If an air separation plant is stopped, the temperature in the PFHE will equalize due to thermal conductivity of the metal and begin to slowly warm up to ambient temperature due to heat leaks in the insulation. During startup, the warm and cold process streams are routed into the PFHE with a relatively high temperature difference between the streams and the PFHE which can cause thermal stress. The level of stress generally increases with the time the process flows are stopped because until equalization, longitudinal heat conductivity increases these temperature differences at both ends of the PFHE.

This behavior should be mimicked in a way that it creates a controlled amount of thermal stress in a relatively small test rig which is not vulnerable to fluctuations in flowrates or temperatures and is economically feasible. It should further cover the temperature range of an ASU heat exchanger of about 100 – 300 K and operate at a pressure level which is common for ASU plants. To achieve maximum accordance between the experimental setup and the model, numerically elaborate conditions like evaporation of pure components should be excluded such that the scenario can be modeled relatively easy and with high accuracy. It is possible to achieve the named tasks by using a two stream PFHE and only one circulated process stream of pure nitrogen.

In the beginning of the test cycle, the PFHE is at a homogeneous warm temperature of 323 K. This temperature slightly exceeds the usual operating range of an ASU but helps to reach the desired level of thermal stress in the test setup. About 1000 kg/h of gaseous N_2 at a temperature of 99 K and a pressure of 5.5 bar serves as the cold stream which is used to cool down the PFHE. During this phase the temperature of the PFHE changes quickly which leads to thermal stress. However, as the PFHE gets colder the temperature difference between the cold stream and metal declines and the rate of temperature change in the PFHE gets smaller. This is why a maximum of thermal stress is reached long before the whole PFHE is cooled down. Figure 1 shows a temperature profile of the test rig after maximum thermal stress has been reached. After that the cooldown phase of the scenario is finished. Because the PFHE is built with sufficient heat capacity and surface area, the cold stream exits the exchanger at the warm temperature of 323 K during this phase. When the cooldown phase is finished, the cold stream supply is stopped. In the second phase, the PFHE is heated up back to 323 K. To achieve this, a stream of N_2 at 323 K is routed to the PFHE at the warm end. To enable for the desired cyclic operation of two parallel test units, the duration of the warmup and cooldown phase should be exactly the same. To make up for the smaller temperature differences during warmup, the warm stream is supplied at an increased flowrate of 10700 kg/h. The higher flowrate and relatively high initial temperature differences lead to very fast temperature change of the metal and the fact that the overall maximum of thermal stress for the whole scenario is reached shortly after switching from cooldown to warmup. After an overall cycle time of 1000 s, the PFHE is back at a homogeneous temperature of 323 K, the warm N_2 flow is stopped and cold N_2 can be applied for the next test cycle.
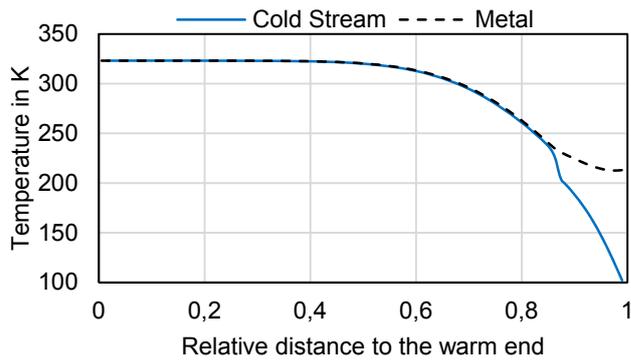
Figure 1: Simulated temperature profile at the end of the cooldown phase

The most wanted scenario in a highly load flexible ASU is a semi-cold restart of a temperature-equalized PFHE where thermal stress can occur at both ends. The fact that the test rig PFHE is homogeneously warmed up and then partially cooled down is related to the generation of comparable thermal stresses as in the field with a relatively small PFHE unit where smaller sizes have to be compensated by an increase of temperature differences.

3.2 Design of a first PFHE specimen

While there are usually many degrees of freedom during the design of a PFHE, the desired test scenario, level of thermal stress and economic feasibility highly constrain this specific specimen. Because large heat exchangers used in ASUs are usually built from several modules which are welded together, each of the two test specimen will also consist of two modules joined by a weldseam in order to cover its effect on the PFHEs lifetime.

Each specimen will have a length of 1.5 m, a width of 0.45 m and a height of 1.6 m. This leads to a weight of about 1500 kg per unit. The design details like fin types, distributors, header and nozzle sizes are chosen as if the test rig was built for use in a real air separation plant. The main challenge for the design is that the flowrate of the warm stream exceeds that of the cold stream by one order of magnitude. This complicates managing the pressure drop in both passages, which is mandatory in order to eliminate any effects of flow maldistribution within the heat exchanger. Hardway fins, which create additional pressure drop where needed, are used to achieve this task. The main target of the test rig is to validate the models and to gain additional information about the damage mechanism. To evaluate the thermal stress of the test rig, knowledge about the exact temperature distribution in the PFHE even in highly dynamic operating conditions is very important. This is why common methods like measuring the temperature at the metal surface is considered to be insufficient for this project. Instead, the temperature on the inside of the soldered block will be measured using fiber glass sensors and several specially prepared dummy layers. This will result in knowledge about the 3D temperature distribution inside the PFHE. However, metal surface temperature will also be measured. Figure 2 shows a photo of one of the two first PFHE units for the test rig during its manufacturing.

Figure 2: Photo taken during manufacturing of the first PFHE specimen

3.3 Layout of the test rig

In order to supply the process streams for the desired test scenario to the two PFHE, some auxiliary equipment is required. Figure 3 shows a simplified process flow diagram (PFD) of the test rig that is reduced to the core components. In the shown state, the PFHE A is in cooldown and PFHE B in warmup phase. Black color indicates a closed valve. Gaseous N_2 is supplied by a "block in kettle" cooler using evaporating N_2 as a coolant. The cold stream flows to one of the two parallel PFHE for its cooldown phase. In the same time, the other PFHE is heated up by a stream of warm N_2 supplied by a heater. The warm outlet stream is split into two parts. The major part is combined with the cold outlet flow, supplied to an electrical heater and a blower which ensure to maintain a temperature of 323 K and pressure of 6 bar for the warm stream by making up pressure drops in the whole test rig. The minor part of the split flows back into the cooler.

It can be seen that due to the cyclic test scenario with equal duration of cooldown and warmup, the cold and warm process streams for the PFHE are both part of one closed circuit. They are continuously supplied to either one of the two parallel PFHE which simplifies the operation of the test rig. Of course, liquid N_2 needs to be supplied to the cooler to achieve the required cooling which is not shown in the simplified PFD.
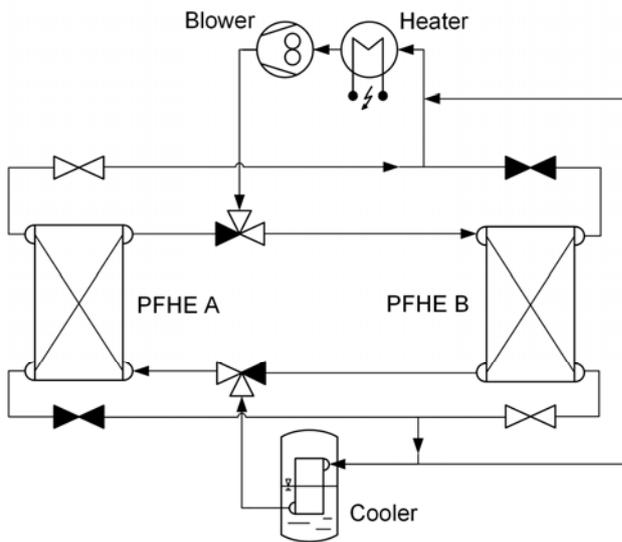

Figure 3: Simplified PFD of the designed PFHE test rig during cooldown of PFHE A and warmup of PFHE B

4. Results

Using the described models for thermohydraulic simulation and FE analysis, the expected lifetime of the PFHE in the test rig can be estimated. Figure 4 shows a qualitative overview of the maximum thermal stress during the designed test scenario.
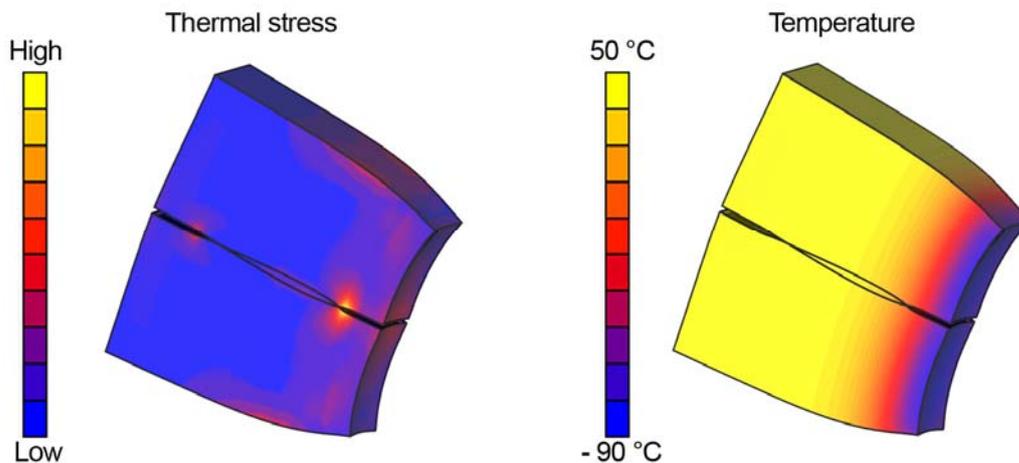

Figure 4: Thermal stress in the test rig according to the model. Note: Deformation is overly exaggerated

Figure 4 shows a relatively high deformation at the cold end of the PFHE which leads to high stresses. The highest stress is located in the vicinity of the welding seam connecting both modules of the test specimen. This shows that it is very important to build the relatively small test rigs out of two modules because otherwise, the location of maximum stress would shift and results could not be transferred to larger PFHE that also consist of multiple modules.

The calculated level of stress in the test rig for this scenario relates to a relatively short expected lifetime. With a cycle time of about 1000 s, first signs of material fatigue in the form of small cracks are expected to show within several weeks of testing. As the test rig is still under construction at the time this paper is written, experimental results on the accordance of the calculated and measured temperature distribution and lifetime of the first test specimen will be published as soon as they are available.

5. Conclusions

The PFHE test rig described in the previous section is unique in its size and the fact that it offers the possibility to gain better understanding of a mechanism that damages large PFHE and cause downtime of ASU plants under well controlled lab circumstances. It has been designed along with the definition of a representative test scenario by using a model specially developed to estimate the lifetime of PFHE by predicting the location and timescale for the occurrence of first small cracks in the test specimen.

The test rig that is under construction at the time this work is written will first be used to verify and improve both steps of the described model for lifetime prediction of large PFHE. It will further be used to qualify improvements in both the design and operating behavior of PFHE for highly flexible operating conditions by designing new test specimen and evaluating their lifetime in the test rig.

Furthermore, the results of the 3D temperature measurement using fiber glass sensors on the inside of the first test specimen can be helpful to improve knowledge about the accuracy of more commonly used techniques like surface temperature measurements for dynamic operating conditions of PFHE.

The detailed insight into the behavior of PFHE in dynamic plant operation gathered from this test rig is an important step towards the goal of a highly flexible ASU. Plant operation is always limited by the capabilities of the PFHE to withstand the resulting mechanical stress. This means that a PFHE model which is well understood and validated is required to optimize the operation of the rectification columns and really maximize the possibilities of using ASU plants to stabilize the power grid.

Acknowledgments

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