International Journal of Heat and Mass Transfer 123 (2018) 523–533

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Improvement of two-phase flow distribution in the header of a plate-fin heat exchanger

Xin-Cheng Tu [a], Yuting Wu [a], Hyoung-Bum Kim [a,b,*]

[a] School of Mechanical and Aerospace Engineering, Gyeongsang National University, Jinju 52828, South Korea
[b] Research Center for Aircraft Parts Technology, Gyeongsang National University, Jinju 52828, South Korea

ARTICLE INFO

Article history:
Received 18 September 2017
Received in revised form 28 February 2018
Accepted 1 March 2018

Keywords:
Plate-fin heat exchanger
PIV
PTV
LIF
Flow distribution

ABSTRACT

The two-phase (liquid and gas) flow distribution in the header of a plate-fin heat exchanger was experimentally investigated. Small mass fractions of the liquid phase in the liquefaction process of natural gas were considered in this study. The liquid and gas flow velocity were measured using optical methods such as PIV/PTV/LIF. The flow maldistribution of liquid and gas flows was quantified and addressing this problem by attaching a porous baffle or modifying the inlet nozzle configuration was studied. The results showed that a vane swirler with a diffuser enhanced the flow distribution of both the liquid and gas phases fluid.

1. Introduction

Combustion of natural gas can greatly reduce the emission of carbon dioxide compared with oil and coal while generating the same amount of energy. Natural gas consumption is predicted to increase at an average rate of around 1.5% per year from 2008 to 2035. It also is replacing traditional oil-based fuels in marine and heavy vehicle engines and power generation and processing industries [1]. Because the liquefaction of natural gas reduces the volume by approximately 600 times, liquefied natural gas (LNG) is economical for transportation and storage.

Heat exchangers play an important role in the liquefaction and regasification process at an LNG plant. A typical multi-stream plate-fin heat exchanger (PFHX) has been commercialized for this plant. The plate-fin heat exchanger is often categorized as a compact heat exchanger to emphasize its high heat transfer surface area to volume ratio. The compactness and low weight help save space and allow application to various facilities, including air separation units, cryogenic liquefaction, and petrochemical and gas treatment plants [2].

An uneven distribution of the fluid in the header part is commonly seen in most multi-passage heat exchangers [3]. Mueller and Chiou [4] summarized the factors that result in a flow maldistribution of the heat exchanger and they can be categorized into two types. The first are mechanical factors such as improper design of the header and distributor, manufacturing tolerances, and plate corrugations. The second are changes of working conditions or fluid properties.

For the conventional header configuration of PFHX, the strong vortex and transverse pressure gradient govern the fluid distribution in the header region. Wen et al. [5] proposed a punched baffle plate in a conventional header to improve the flow maldistribution. Ismail et al. [6] adopted a similar porous baffle to evaluate the geometry-induced maldistribution effect. Besides the installation of the baffle plate in the header, modifications of the header shape such as a two stage header structure [7], a complementary fluid cavity [8], and a streamlined header [9] were proposed.

This literature survey of the flow maldistribution in a PFHX reveals that modification of the header or the addition of a baffle were effective means to improve the flow distribution. However, most of these studies only dealt with the distribution of a single phase flow. The distribution of a two-phase flow is quite different and affects the thermal performance of a PFHX. Therefore, it is necessary to investigate the two-phase flow distribution in the header of a PFHX.

For the two-phase flow condition in a PFHX, a uniform distribution in the header is important to obtain a homogenous phase change. Compared with a single phase flow, maldistribution of a two-phase flow was severe [10]. Due to the large momentum of the liquid phase, the liquid and gas flow distributions are quite

* Corresponding author at: School of Mechanical and Aerospace Engineering, Gyeongsang National University, Jinju 52828, South Korea.
E-mail address: kimhb@gnu.ac.kr (H.-B. Kim).

https://doi.org/10.1016/j.ijheatmasstransfer.2018.03.001
0017-9310/

different. Yuan et al. [11] developed a separated inlet structure to improve the flow distribution. The liquid phase directly enters the distributor chamber and mixes with the gas just before the fin passages rather than in the header.

From these investigations of a two-phase flow in a PFHX, severe deterioration of flow distribution was observed. However, little research has been carried out to reveal the flow structure and the flow distribution in the header part, particularly when the liquid mass fraction is especially small. This smaller liquid mass fraction is a typical characteristic of the liquefaction process of a LNG plant.

In this paper, we investigated the two-phase flow distribution in the header of a PFHX by measuring the velocity fields of the gas and liquid phases simultaneously. We presented the quantitative results to improve the distribution of the two-phase flow.

2. Experimental method and apparatus

The detailed geometry and experimental setup of the PFHX model used in this study is shown in Fig. 1. It is a 1/6 scale-downed model from the proto-type PFHX used in the LNG plant. The plate-fin area is simplified in this model. The entire dimensions of the experimental apparatus are normalized by the radius (R = 13 mm) of the neck of the Venturi tube which is explained in the following paragraph.

Water and air were used as working fluids instead of natural gas and LNG. When the liquid and gas phases of natural gas flow into the header, the liquid phase flows along the bottom wall and drops directly down to the bottom part of the header due to gravity. This liquid stream causes a severe maldistribution of the liquid fluid. We modified the inlet pipe section from the straight shape to a venturi shape and supplied the liquid to this venturi neck. This venturi inlet generated the water droplets. That is, gas and water droplets enter the header region. The venturi tube design fulfills the requirements of the ISO 5167-4 standard.

During the operation of the proto-type PFHX, the mass fraction of the liquid to the gas phase varies from 0.1 to a maximum of 20%. Compressed air supply was used for supplying air, and the flow rate was adjusted by an air regulator. Pressure and temperature sensors and a flow meter were installed to measure the air mass flow rate. The volume flow rate of the liquid phase is controlled by a peristaltic pump. In the present study, the mass flow rate of the gas phase was kept at a constant value of 340 g/min.

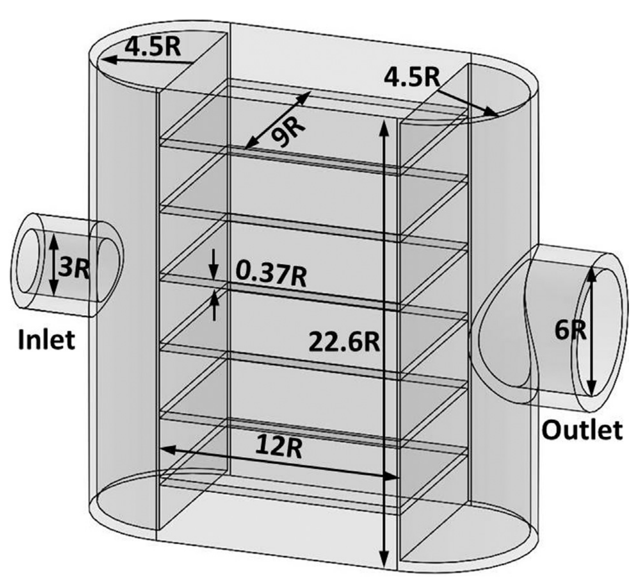

Fig. 1. Schematic of scale-downed PFHX model with simplified plate-fin area (R = 13 mm).

From the preliminary study, we found that if the mass fraction of liquid is larger than 5%, the venturi tube cannot make water droplets and the liquid stream reappeared at the inlet. Therefore, the experiments were performed under a 5% liquid mass fraction.

In order to investigate the two-phase flow characteristics in the header, simultaneous measurement of liquid and gas velocity is necessary. Many studies have been carried out to measure two-phase flow velocities simultaneously. Rottenkolber et al. [12] used a single camera system equipped with a high-pass filter to capture images of the mixture phase. Lindken et al. [13] took advantage of a combination of a digital mask with the MQD method to separate the bubble or solid particle images with tracer particles of the liquid phase. Driscoll et al. [14] developed a two-laser & two-camera system to measure a dense fuel spray.

Although there are some variations of the apparatus and algorithms, most use optical and fluorescent imaging methods, and the PIV/PTV were applied to calculate the velocities of different phases. The separation between the liquid and gas phases is based on using the color (wavelength) or geometry (size) information in general. In this study, we used the LIF method to identify the liquid phase.

Fig. 2(a) shows a schematic diagram of the experimental apparatus. We visualized the gas phase by using olive oil droplets generated from a Laskin nozzle. The liquid phase is atomized into water droplets in a venturi neck and mixed with the gas phase in the throat part. The water droplets were tagged by Rhodamine B to provide droplet images at a higher wavelength than the olive oil particles. Two CCD cameras of 1.6 K $\times$ 1.2 K pixel resolution, CCD 1 and CCD 2, are installed at two opposite locations to capture images of the liquid phase and mixture phase (Fig. 2(b)). They are aligned in the same normal axis to the measurement field. CCD 2 was equipped with a band-pass filter to capture the filtered light from a water droplet image. The other camera, CCD 1, directly received Mie scattering light from the olive oil droplet and fluorescent light remitted from tagged water droplets. The field of view (FOV) for these two cameras is correlated by a coordinate transform matrix made from the calibration process. Two cameras captured the calibration images of the same target at the laser sheet plane. According to the coordinates of the same marked points from two respective calibration images, the transform matrix of coordinates and magnification due to the geometric distortion can be deducted. CCD 3 was only used for the gas phase velocity measurement near the top region of header. All cameras were synced with a Nd:YAG laser and a pulse generator controlled the laser and the CCD camera system.

In this experiment, we used the simple subtraction method to obtain the gas phase flow images. The differences in size and shape between water and oil seeding particles were not distinct. Therefore, it is difficult to separate the liquid droplet images from the mixture phase images. Fig. 3 shows the applied image processing method for the phase separation procedure. We processed the water droplet image of the LIF configuration to obtain the centroid using the local thresholding method. The pixel information of the water droplet centroid and the geometry are then transformed by the transformation matrix from the camera calibration test. The particle image from the PIV configuration could be marked according to the transformed centroid pixel information of the corresponding LIF image. The marked droplets are finally removed. The area of the subtracted liquid droplet image was replaced by the mean value of the local background intensity.

The conventional cross-correlation based DPIV method to obtain the instantaneous velocity vector fields of the gas phase flow was used. The size of the interrogation window is 32 $\times$ 32 pixels with 50% overlapping. The average properties were calculated