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Passive control of gas–liquid flow in a separator unit using an apertured baffle in a parallel-flow condenser

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ABSTRACT

A transparent separation unit with an apertured baffle for liquid–gas separation was constructed using acrylic resin. The phase-separation characteristics were examined using air and water as working fluids. The drain limit, flooding limit, and liquid level in the header of the unit were determined under different inlet liquid and gas superficial velocities. The performances of the unit were evaluated by analyzing the effects of pressure, gravity, and capillary force. The liquid-separation efficiency of the separator was determined by the inlet flow patterns. The unit showed strong liquid–gas separation effects at optimal inlet conditions. The liquid-separation efficiency was higher than 45% for an annular flow inlet, higher than 80% for a slug flow inlet at low liquid inlet superficial velocities, and approached 100% for a stratified flow inlet. The flow distribution in the header was visually observed using a high-speed camera to determine the effects of the inlet flow patterns on the drain limit as well as on the liquid-separation efficiency.

1. Introduction

Parallel-flow condensers are generally used in domestic and industrial applications. These condensers exhibit superior thermal performances compared with conventional heat exchangers. However, this condenser type has two disadvantages. One is the grouping of several tubes into one pass, which results in a lower mass flow rate and leads to heat-transfer deterioration. The other is the non-uniform working-medium distribution between the different tubes and passes of the condenser as a result of the density differences between the liquid and vapor phases of the working medium. This non-uniform distribution also reduces the thermal and fluid-dynamic performances of the condenser [1]. The heat-transfer performance decreases [2] by as much as 25% through flow maldistribution [3].

Numerous attempts have been made to improve the heat transfer of heat exchangers. A review paper [4] classified the heat-transfer augmentation methods into three categories: active method, passive method, and compound method, which is a combination of the first two methods. An active method requires an external activator or power supply to enhance heat transfer. A passive method uses an enhancing heat-transfer surface or inserts to increase the heat-transfer coefficient; however, this method increases the friction factor and the pressure drop which eventually leads to higher pumping costs [4,5].

Researchers also attempt to improve the maldistribution of the working medium in parallel-flow heat exchangers. The methods are mainly classified into two categories. The first involves the introduction of an intensively (or thoroughly) mixed gas and liquid phases [6]. However, this technique generally fails to produce a uniform distribution under the operating conditions [7]. The other method involves the separation of the vapor or liquid working medium prior to the flow distributions to ensure that only one phase of the working medium enters the condenser. This technique is based on the generally accepted concept that inlet mass quality significantly affects the flow distribution in a compact heat exchanger [2,3,8]. Lee [3] found that variations in the distribution curve along the flow direction decreases with increasing inlet quality. Ahmad et al. [8] reported the strongly positive effect of increasing the inlet mass quality on the two-phase distribution. In a recent study, Zhang et al. [9] demonstrated that the remaining gas-rich flow can be uniformly distributed into the primary distribution branches after most of the liquid is removed from the mixture via partial separate-phase distribution using a dual-header distributor.

An innovative idea was recently proposed to design a new type of high-performance condensers using several simple gas–liquid separators [10]. A liquid–vapor separation condenser (LSC) can automatically separate liquid from a gas–liquid mixture or a two-phase flow during condensation. This liquid–gas separation condenser has been introduced in a previous study [11]. Fig. 1a

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Nomenclature

D	header inner diameter (m)
d	side arm inner diameter (m)
D_d	diameter of the hole in the baffle (m)
G	mass flow rate (kg/s)
g	acceleration of gravity (m/s^2)
H	header height (m)
h	height of the liquid level (m)
H_2	pitch of arm tubes (m)
H_1	lower-arm height from the bottom of the header (m)
H_d	depth of the hole in the baffle (m)
L_i	upper arm length (m)
L_o	lower arm length (m)
p	pressure (Pa)
Δp	pressure difference (Pa)
Re	Reynolds number, dimensionless
u	superficial velocity (m/s)
We	Weber number, dimensionless

Greek symbols

η	liquid-separation efficiency, dimensionless
μ	viscosity (Pa s)
ρ	density (kg/m^3)
σ	surface tension (N/m)

Subscripts

an	annular flow
fl	flooding
g	gas
gr	gravity
in	inlet
l	liquid
st	stratified flow

shows the configuration of the LSC. The LSC consists of a parallel-flow arrangement with a pair of headers and a tube bank with U-bends. Several baffles with a number of apertures (0.5–2 mm in diameter) are set in the headers. The apertured baffles serve as gas–liquid separators. The condensate flows directly through the apertured baffles to the bottom of the header and allows high-quality vapor to enter the subsequent pass. Consequently, condensation always occurs at high-vapor qualities, and a higher heat transfer coefficient and lower pressure drop are achieved in the entire condensation zone. The excellent performance of an air-conditioning system equipped with an LSC was validated by a series of experiments [11]. However, the phase-separation characteristics of these novel condensers remain unclear.

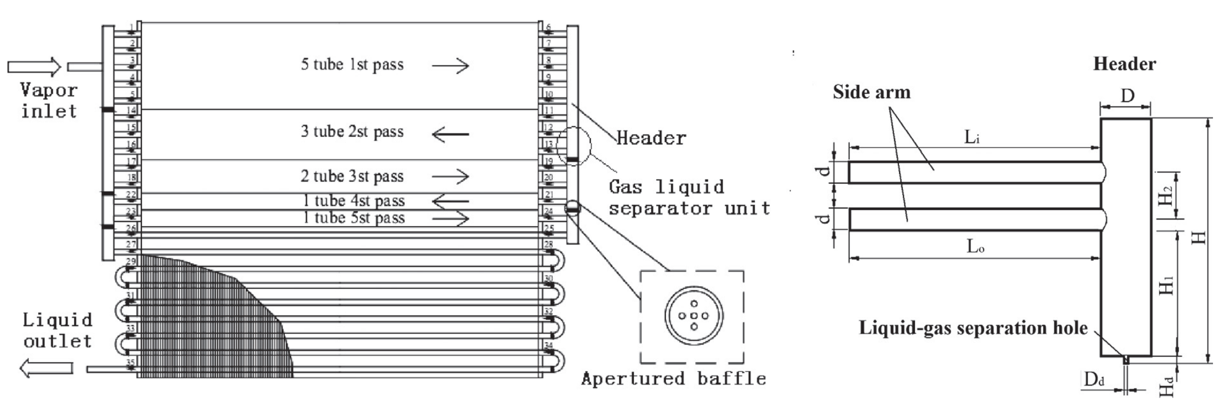
The gas–liquid separator is a key unit in the LSC. To date, no research has focused on the use of a gas–liquid separator unit with an apertured baffle for liquid separation. Fig. 1b shows a simple gas–liquid separator unit that has only one hole in the apertured baffle for liquid separation. The gas–liquid separator unit resembles two combined T-junctions except for the apertured baffle. The two-phase flow in the T-junctions or in the header of a parallel-flow heat exchanger is complex. Several studies have been conducted on the orientation (parallel, normal, or vertical) [12–15], geometric parameters (e.g., side tube/header size, protrusion depth of the side tube into the header, and sizes of insertion devices) [16–18], working conditions (gas- and liquid-phase flow rates), and the combination of two or more of these factors [1,19–21]. In this study, the effect of the apertured baffle of the gas–liquid separator on the flow in the separator is vital to phase separation and thus requires further analysis.

In this study, the phase-separation characteristics of the gas–liquid separator unit under different inlet flow conditions were investigated. The pressure, gravity, and capillary force in the separator were analyzed to determine the separation characteristics. The internal flow distribution in the unit header was visually observed to evaluate the phase-separation performance under different inlet flow patterns. The results may be applicable to other compact separators.

2. Experimental system

2.1. Separation unit

The gas–liquid separator unit was designed based on the LSC. A detailed structure of the separator unit is shown in Fig. 1b. The condenser was simulated by allowing the gas–liquid mixture flow into the upper arm and then separating the two phases in the header (main vertical pipe). The outside portion of the header had a rectangular cross-section to minimize refraction errors



(a) Gas–liquid separation condenser (b) Gas–liquid separator unit

Fig. 1. Separator unit configuration.