INVESTIGATION STUDY OF THE INLET TO BODY DIAMETER RATIO OF A VERTICAL FLASH TANK SEPARATOR USING COMPUTATIONAL FLUID DYNAMIC (CFD)

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Abstract - The vertical flash tank separator improves the heat transfer coefficient in the evaporator of the mechanical refrigeration system. However, enhancing and improving the performance of the vertical flash tank separator need further investigation. In order to provide an optimum design and performance of a vertical flash tank separator, this paper provides an investigation study to present the effect of the inlet to body diameter ratio (d/D) of the vertical flash tank separator on the separator's performance. Computational Fluid Dynamic (CFD) was used to design the optimum ratio configuration. The results revealed that the d/D has significant effect on the liquid separation efficiency. The CFD simulations give a good agreement with the experiments, all the simulations underestimated the liquid separation efficiency by approximately 0.02 over the range of conditions tested.

Keywords - Vertical Flash Tank, Liquid Separation Efficiency, Optimum Design of Separator, CFD Simulations

I. INTRODUCTION

The vapour injection technique using a vertical flash tank is an effective way to enhance the system's coefficient of performance (COP). A flash tank feeds the evaporator with the separated liquid, and the vapour is injected into the compressor[1, 2]. Therefore, enhancing the performance of the vertical flash tank separator will enhance and improve the overall system performance[3]. Adding the vertical flash tank separator to the mechanical vapour systems, can play a role in enhancing the cooling capacity and system performance [4]. Grodal and Realff [5] suggested using a wire mesh and mist extractor to separate the liquid drops that move with the gas through the gas outlet as it is not economic to separate these drops by gravity alone by making the separator larger.Hanfei and Hrnjak [4] presented experimental work investigating the phase separation enhancement in a vertical gas-liquid separator. The results revealed that the liquid impingement on the wall of separator has a significant effect on the separation efficiency.
Some researchers used refrigerant R134A to investigate the separation efficiency in a vertical separator such as Hanfei and Hrnjak [4] and Zheng, Zhao [6] or used different configuration of the vertical separator such as Wang [7] and Grodal and Realff [5]. CFD simulation is a appropriate way to investigate the two-phase flow behaviour and it can be used as design tool [8].
[9] presented a CFD study to simulate the two-phase flow inside a cyclone separator and to optimize the geometry of the cyclone separator. Four main geometrical parameters were considered in the numerical optimization: core diameter, number of vanes, height of vanes and leading edge angle. The results indicated that the most significant geometrical parameters of the cyclone separator are the number of vanes, the vane angle and the vane height. A new optimised geometry was obtained from the CFD simulation but it was not validated with experimental results.
[10] used CFD simulation to investigate the two-phase flow inside a swirl-vane separator and to analyse the separation performance. A mixture of air and water was used as the working fluid. The results revealed that the separation efficiency of the swirl-vane separator depends on the flow pattern and the water velocity, while the pressure drop is mainly affected by the air flow rate and water droplet diameter. The CFD simulation results apparently agreed with the experimental results, but the difference between the CFD simulation and experimental results was not quantified.
From the existing studies, there is a further need to establish fundamental design options for optimising the vertical flash tank separator and its configurations that can be used to enhance the separation performance. This paper presents a CFD instruction to simulate and investigate the effect of the inlet to body diameter (d/D) ratio of the vertical flash tank separator using ANSYS 17.1 with Fluent to carry out the simulations and present the result using post processing. This work also provides CFD data that contributes additional knowledge for flash tank design using water as the working fluid. The simulation process starts with design modeller to creat a 3D vertical flash tank separator. Then, generat mesh by using ANSYS meshing and finally proceed the solution via ANSYS Fluent.

II. GOVERNING EQUATIONS

In order to present two-phase flow equations, q and p will be used to describe liquid and gas phases respectively. The general form of the two-phase governing model can be presented as follows.

The continuity equation for phase q can be presented as following.

$$\frac{\partial}{\partial t}\left(\alpha_q\rho_q\right)+\nabla.\left(\alpha_q\rho_q v_q\right)=\sum_{p=1}^{n}\left(m_{pq}-m_{qp}\right)+S_q \quad (1)$$

[11] defined the volume fraction for the individual phase as the volume occupied by that phase. So the volume of the phase q can be given by.

$$V_q=\int \alpha_q dV \quad (2)$$

Where

$$\sum_{q=1}^{n}\alpha_q=1 \quad (3)$$

Accordingly, the volume fraction of the gas phase can be given by

$$\alpha_q=\frac{Q_q}{Q_t}=\frac{V_q}{V_t} \quad (4)$$

According to [12], the Conservation of momentum can be written as:

$$\frac{\partial}{\partial t}\left(\alpha_q\rho_q v_q\right)+\nabla.\left(\alpha_q\rho_q v_q v_q\right)=-\alpha_q\nabla p+\nabla.\tau_q+\alpha_q\rho_q g+\sum_{p=1}^{n}\left(R_{pq}+m_{pq}v_{pq}-m_{qp}v_{qp}\right)+\left(F_q+F_{lift,q}+F_{vm,q}\right) \quad (5)$$

Where τ_q is the q phase stress-strain tensor, given by:

$$\tau_q=\alpha_q\mu_q\left(\nabla.v_q+\nabla.v^T{}_q\right)+\alpha_q\left(\lambda_q-\frac{2}{3}\mu_q\right)\nabla.v_q I \quad (6)$$

In Equation 6 above, λ_q and μ_q are the shear and bulk viscosity of phase q, R_{pq} is an interaction force between phases, p is the pressure shared by all phases and v_{pq} is the interphase velocity which can be defined as: $v_{pq}=v_p$; for $m_{pq}>0$ and $v_{pq}=v_q$ for $m_{pq}<0$, likewise, if $m_{qp}>0$ then $v_{qp}=v_q$, and $if\, m_{qp}<0$ then $v_{qp}=v_p$ [12]. The momentum equation has to be closed with appropriate expression for the inter-phase force R_{pq}. This force depends on the pressure, friction and cohesion in addition to other effects. This closure can be satisfied by: $R_{pq}=-R_{qp}$ and $R_{qq}=0$.

In order to achieve a correct solution, simple iteration is available which can be defined as.

$$\sum_{p=1}^{n}R_{pq}=\sum_{p=1}^{n}K_{pq}\left(v_p-v_q\right) \quad (7)$$

The lift force, shown in Equation 5, acts on the secondary phase particles, droplets or bubbles, by virtue of the velocity gradients. The lift force becomes significant when the particle size is large, however, the assumption, in the numerical model solution, that the particles size is much smaller than the inter-particle spacing may lead to the exclusion of the lift forces from equation 5.

Terzuoli et al. (2008) defined the lift force acting on a secondary phase p in a primary phase q as:

$$F_{lift}=-0.5\rho_q\alpha_q\left(v_q-v_p\right)\left(\nabla.v_q\right) \quad (8)$$

Virtual mass force is another force that is included in the momentum equation. It acts on the two-phase flow when the secondary phase p accelerates relative to primary phase q [13]. Accordingly, the effect of virtual mass force will be significant when the density of the secondary phase is much smaller than the density of the primary phase. The virtual mass force can be presented as follows.

$$F_{vm}=0.5\alpha_q\rho_q\left(\frac{d_q v_q}{dt}-\frac{d_q v_p}{dt}\right) \quad (9)$$

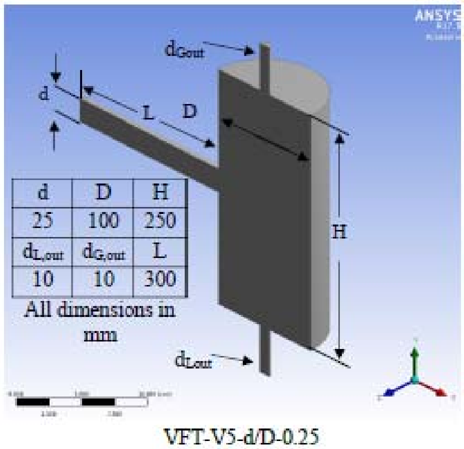
The derivative in Equation 9 is the phase material derivative which can be presented as [12]:

$$\frac{d_q(\emptyset)}{dt}=\frac{\partial(\emptyset)}{\partial t}+\left(v_q.\nabla\right)\emptyset \quad (10)$$

$$\frac{d_q(\emptyset)}{dt}=\frac{\partial(\emptyset)}{\partial t}+\left(v_q.\nabla\right)\emptyset \quad (11)$$

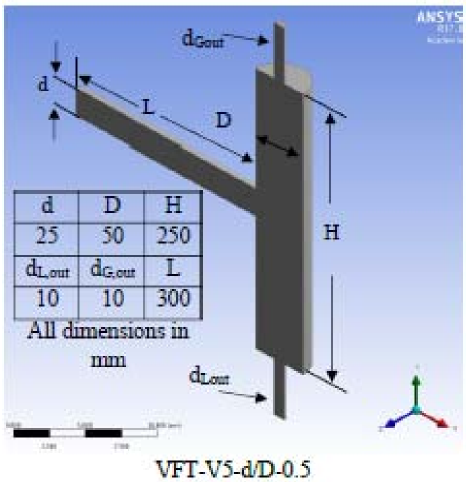
GEOMETRY

Three geometries of the vertical flash tank separator (VFT) were generated using design modular of the ANSYS 17.1. The geometries were created in three different sizes based on the ratio of the inlet to body dimeter (d/D); d/D=0.25, d/D=0.5 and d/D=1. There was no separation enhancer installed inside the vertical separator tank. The separator has two outlets: the liquid outlet, which is at the bottom of the tank and has a 10 mm inside diameter ($d_{L,out}$) , and the gas outlet, which is at the top of the tank and also has a 10 mm inside diameter ($d_{G,out}$).The length of the inlet tube of the vertical flash tank separator was 300 mm. Fig.1, Fig.2 and Fig.3 show the three geometries of the vertical flash tank separator and its dimensions.



d	D	H
25	100	250
dL,out	dG,out	L
10	10	300

Fig. 1 GEOMETRIES OF THE VERTICAL FLASH TANK SEPARATOR CREATED IN D/D=0.25 , VFT-V5-D/D=0.25



d	D	H
25	50	250
dL,out	dG,out	L
10	10	300

Fig. 2 GEOMETRIES OF THE VERTICAL FLASH TANK SEPARATOR CREATED IN D/D=0.5, VFT-V5-D/D=0.5

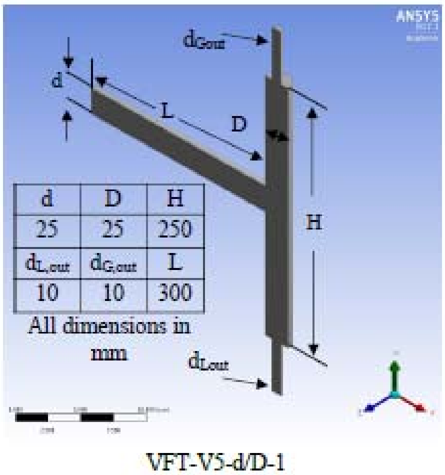


Fig. 3 GEOMETRIES OF THE VERTICAL FLASH TANK SEPARATOR CREATED IN D/D=1, VFT-V5-D/D=1

III. MESH GENERATION

3.1 Mesh quality

The meshes created for the vertical flash tank separator simulations were created from tetrahedral elements which has benefits such as reduced computational time and improved mesh quality for three dimensional domains of complex shapes.The mesh quality can be represented by three factors namely, orthogonal quality, aspect ratio, and skewness value[9]. The orthogonal quality ranges from 0 to 1 and 0 represents low mesh quality. The minimum orthogonal quality should always be greater than or equal to 0.01. The aspect ratio is relevant to the wall function and should be small enough to allow the solution to capture the flow details near the wall. The skewness value, which is inversely related to solution accuracy, should be small enough to minimize error in the solution [10]. For the mesh used in the present simulations, the orthogonal quality was 0.9 with a minimum value of 0.07, the aspect ratio was 3.56, and skewness value was 0.26. These values indicate that according to the established criteria, good mesh qualities were obtained and used in the present simulations.

3.2 Mesh independence study

The geometries of the vertical flash tank separator were discretised into tetrahedral elements and in order to generate a fine mesh near the walls, the inflation method was used. Four computational grids of 8500, 180000, 220000 and 280000 were used to investigate the grid independence for all geometries of the vertical flash tank. The Fig. 4 illustrates the significant effect of the different element numbers on the resolution of the interface of two-phase flow, based on liquid volume fraction distribution. It can be seen that there is no significant change in the liquid volume fraction and the smoothing of interface between the liquid and vapour when the mesh number increased beyond 220000.

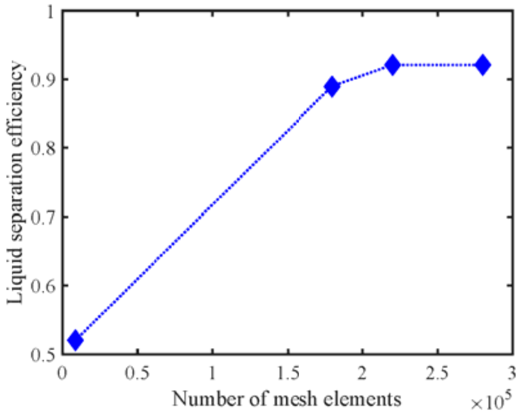


FIG. 4 ASSESSMENT OF GRID INDEPENDENCE FOR THE VERTICAL FLASH TANK SHOWING VARIATION OF LIQUID SEPARATION EFFICIENCY WITH NUMBER OF MESH ELEMENT

IV. BOUNDARY CONDITIONS

In order to generate simulations consistent with the experiments data, the experimental operating conditions, which are related to this study, were used in the CFD simulation. Water was used as the working fluid. At the inlet, the liquid droplet size is selected according to the expansion device design which has 400 holes with 0.3 mm diameter, so the liquid droplet diameter is selected to be 300 µm.

The inlet boundary condition was specified as uniform velocity distribution for each phase at the inlet of the horizontal tube. A pressure outlet was used for the outlet boundary condition. The no slip wall was applied for the wall boundary.

V. RESULTS AND DISCUSSION

The mass flow rate was the parameter that was changed in the experiment. Hence the variation of the liquid separation efficiency with the inlet mass velocity for the vertical flash tank separator VFT-V5d/D=0.5 is presented in Fig. 5. Generally, the results revealed that the liquid separation efficiency increased gradually as a result of increasing the inlet mass flow rate. The results also revealed that the liquid stream impingement on the inner side of the separator increased when the inlet mass flow rate increased. The trend of the numerical results is similar to that in the experimental results and good agreement was observed between the numerical and experimental results. However, the simulations consistently underestimate the separation efficiency by an amount that varies between about 0.01 and 0.02. For example, in the highest separation efficiency, which was achieved by VFT-V5d/D=0.5 at an inlet mass velocity of 44.23 $kg/m^2.s$, the experiment gave 0.96 whereas the simulation indicated 0.94.

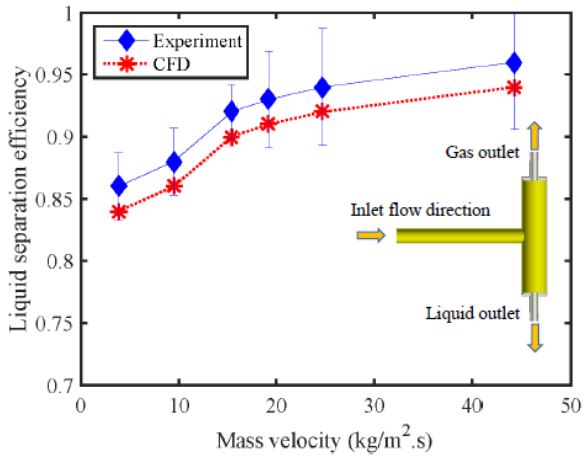


Fig. 5 NUMERICAL AND EXPERIMENTAL RESULTS FOR LIQUID SEPARATION EFFICIENCY WITH VFT-V5D/D=0.5

Fig.6 presents the results from the CFD simulations of the three ratios of d/D. The liquid separation efficiency for d/D = 1 decreases with increasing mass flow rate, a result which is the same as that obtained by [4]. The reason for this effect is that when the mass flow rate increased, the two-phase velocities increase and a point is reached where the liquid inertia force and vapour drag force gradually dominate the gravitational force [4]. When a portion of the incoming liquid stream diverts into the upward direction after impingement on the wall, a portion of separator's cross-section area is further reduced, and consequently the local velocity of the vapour increases and thus, the drag force also increases. Therefore, as more liquid moves with the gas through the gas outlet for d/D = 1, the liquid separation efficiency is decreased. For d/D = 0.25, the liquid separation efficiency is about 3.5 % higher than that for d/D = 0.5. In both cases, the efficiency increases with increasing mass flow rate.

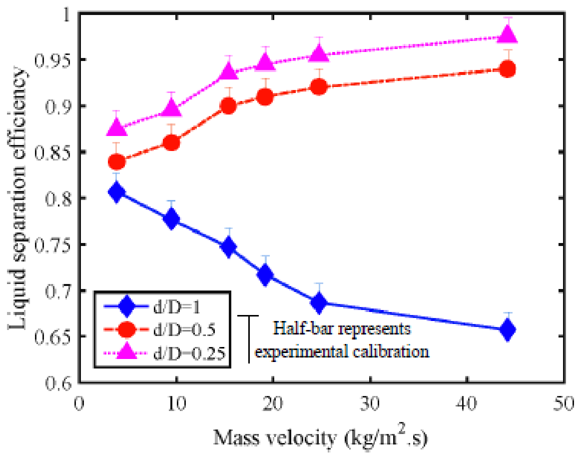


Fig. 6 COMPARISON OF NUMERICAL RESULTS SHOWING THE EFFICIENCY OF D/D RATIO

According to the comparison between the experimental and numerical results of the VFT-V5d/D=0.5 (Fig.5), the CFD underestimated the data by about 0.02. This value has been used as a calibration offset for the results of the virtual experiment and so the half-bars on the Fig. 4 represents the expected increase in efficiency if physical experiments were actually performed.

Although VFT-V5 with d/D = 0.25 offers superior performance, the VFT-V5 configuration with d/D = 0.5 was used for testing the enhanced design options to improve the efficiency of the liquid separation for two reasons. Firstly, the behaviour of the separation efficiency ford/D = 0.25 is very similar to d/D = 0.5, only the d/D = 0.25 gives 3.5 % improvement in efficiency relative to d/D = 0.5. Secondly, as the VFT-V5 with d/D = 0.5 already exists with its components and accessories such as the aluminium flanges and its O-ring for the related study, the extra costs to perform the experiments on d/D = 0.5 were only marginal.

CONCLUSION

Numerical and experimental investigations of the liquid separation efficiency of a vertical flash tank separator have been performed for a range of mass flow rates. Outcomes can be summarized as below.

1. The highest value of the liquid separation efficiency was achieved by the VFT-V5d/D=0.25 configuration.
2. Liquid stream impingement on the inner side of the separator increased when the inlet mass flow rate increased.
3. All the experimental results of the liquid separation efficiency using the VFT-V5d/D=0.5 vertical separator have been compared with the numerical results at the same operating condition. The simulations underestimated the liquid separation efficiency by approximately 0.02 over the range of conditions tested.
4. Through CFD virtual experiments, the d/D ratio is demonstrated to have a significant effect on the liquid separation efficiency. The liquid separation efficiency is decreased when the d/D ratio is increased.

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