Effect of triangular corrugations on dynamic characteristics of film flow

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Abstract

Thick film flow in a narrow channel is investigated by simulations and experiments. The influence of obstacle and corrugations on liquid film flow is studied in simulations. LIF (light induced fluorescence) method is applied to visualize the flow field close to the substrate in the experiments. With the validated 3-D simulations, numerical investigation of film flow over triangular corrugations can be done. The results indicate that eddies in the trough of corrugations are generated in two ways. Eddies generated in the first way are mainly induced by the geometry of the substrate with strong undulated corrugations. On corrugations with a small steepness, eddies generated in the second way are primarily induced by inertia force and their formulation are depended on Reynolds number. Whenever corrugations are steep or smooth, eddies in the troughs always have two variation periods with regard to Reynolds number. In the first period, the eddy size enlarges dramatically with increasing Reynolds number. In the second period, increasing Reynolds number has little influence on the eddy transformation. A smooth corrugation will delay the transition point of the two periods, and reduce the difference between them. Film flow over arbitrary geometric corrugations is simulated and the stagnant point movement is investigated. Similarity theory in fluid dynamics is verified, which proves that results of this study with relatively large scale model provides basic knowledge that can be used to predict flow behavior in small scale corrugated plates in industry.

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Keywords: Film flow; triangular corrugations; VOF (volume of fluid); LIF (light induced fluorescence)

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1. Introduction

Film flow accompanied with mass transfer is encountered in many industrial chemical equipments, such as distillation and absorption towers. J.-U. Repke et al. [1, 2] and O. Villain et al. [3, 4] have carried out extensive investigations on three-phase distillations. The results demonstrate that even the same component mixture will have discrepancy and multiplicity in the distillation process. Mass transfer efficiency which is influenced significantly by the behavior of the film flow is of importance in these equipments. L. Chen et al. [5, 6] have figured out that the effective interfacial area between gas and liquid is the most dominating transfer parameter. Recently, a few experimental and CFD studies about the flow behavior on packing surface have been carried out by A. Hoffmann et al. [7, 8], J.-U. Repke et al. [9] and Y. Xu et al. [10, 11]. Flow behavior including film breakup, rivulet-flow and count-current gas flow is deeply investigated in these studies. The results can be applied as fundamental assumptions in the

<table>
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<th>Nomenclature</th>
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<td><strong>Re</strong></td>
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<td><strong>μ_w</strong></td>
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<td><strong>μ_air</strong></td>
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<td><strong>ρ_w</strong></td>
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<tr>
<td><strong>ρ_air</strong></td>
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<td><strong>σ</strong></td>
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<td><strong>α</strong></td>
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<td><strong>M_{3d}^w</strong></td>
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<td><strong>M_{2d}</strong></td>
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<td><strong>L’</strong></td>
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investigation of mass transfer. In order to increase mass transfer in industrial applications, a variety of structured packings are used. The structured plates often consist of big undulations and small corrugations on them. A. Wierschem et al. [12] and Yu. Ya. Trifonov [13] have shown that the small corrugations stabilize film flow and suppress the formulation of waves on the free surface. Therefore these small corrugations actually reduce the area of free surface. M. Kohrt et al. [14] also proved this phenomenon in their study, that the area of free surface of film flow on corrugated plates and flat plates is very similar. However, mass transfer can be tremendously improved by the corrugated plate [15]. This means flow transition caused by corrugations has a significantly influence on the enhancement of mass transfer. The principle of the flow regime variation on corrugations is still not well studied, which is the subject of this paper.

In recent years, film flow over sinusoidal corrugated plate has been investigated by several researchers. S. Negny et al. [16, 17] studied the thin film on vertical sinusoidal corrugations. He used an optical method to measure the film thickness and validated his simulations. A. Wierschem et al. [18-20] investigated film flow on sinusoidal corrugated plates with both experiments and simulations. In his experiments, the flow field is measured with PIV (particle image velocimeter) method, which has a good agreement with his simulation results. M. Scholle et al. [21] and P. K. Nguyen et al. [22] also investigated gravity driven film flow on sinusoidal corrugated plate. Other researchers focus on film flow over rectangular corrugations. M. Vlachogiannis et al. [23] used a fluorescence imaging method to measure the free surface position and analyzed the stabilization of film flow. K. Argyriadi et al. [24] also investigated the effect of corrugation steepness and found steep corrugations expand the stable region of steady flow significantly. M. I. Pak et al. [25] applied VOF (volume of fluid) method to simulate the film flow along a substrate with rectangular corrugations. Y. Haroun et al. [26] carried out a numerical investigation of film flow over triangular corrugations. Mass transfer is included in their numerical model. The results show that mass transfer is not directly affected by the recirculation in the corrugation cavities but linked to the interface shape that controls the exposure time.

The investigations that have been carried out are mainly on sinusoidal and rectangular corrugations. Only a few studies on triangular structured plates are known. In this paper, film flow over triangular corrugations is deeply studied with both CFD (computational dynamic fluid) simulations and experiments. To focus on the flow field close to substrate and remove the surface tension effect, flow with increased film thickness is considered. In future investigations, film flow with a small thickness will be included. In the simulations, VOF (volume of fluid) method is applied to investigate the influence of obstacle and corrugations on liquid film flow. In the experiment, LIF (light induced fluorescence) method is used to visualize the flow field close to the corrugations.

2. Simulations and their validation with experiments

2.1. Model to be simulated

The dimensions of the corrugations on structured plates in industrial equipments are often less than 1mm, which causes difficulties in the measurement of eddies in the trough of the corrugations. To get more precise results and have a fundamentally understanding, corrugations investigated in this study are about 10 times larger than that on practical packing plates. Basic phenomena will be studied here based on fluid similarity theory. Figure 1 shows the schematic of the model that will be investigated by both simulations and experiments. The height of the channel is 50mm, and the triangular corrugations are 10mm tall. The base angels of the triangular corrugations are 45°. The width of the channel is 5mm to make it easier to use LIF to visualize the flow field close to the substrate. To remove the effect from the inlet and outlet, two long transitional regions are designed on the both sides of the test region. The
channel is horizontal with a length of 500mm and the corrugations are in the middle. The film flow in the channel is very thick (at least 30mm) to remove surface tension effect and to focus on the eddy formation in the trough of the corrugations. The properties of the fluids (water and air), which are taken from OpenFOAM library, are listed in table 1. The hydraulic diameter in the partly filled rectangular channel is used to calculate Reynolds number.

Table 1. Properties of the fluid in the channel

<table>
<thead>
<tr>
<th>Reynolds number</th>
<th>Kinematic viscosity(m²/s)</th>
<th>Density(kg/m³)</th>
<th>Surface tension(N/m²)</th>
</tr>
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<tr>
<td>Re =16, 158, 316</td>
<td>µ_w=1.0×10^-6</td>
<td>ρ_w=1000</td>
<td>σ=0.07</td>
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<tr>
<td></td>
<td>µ_air=1.48×10^-5</td>
<td>ρ_air=1</td>
<td></td>
</tr>
</tbody>
</table>

A multiphase solver in OpenFOAM named interFOAM is applied for modelling and simulations. In interFOAM, the free surface of the film flow is tracked with VOF method. The boundary conditions are listed in table 2.

Table 2. Boundary conditions of the model

<table>
<thead>
<tr>
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<th>inlet</th>
<th>outlet</th>
<th>wall</th>
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<tbody>
<tr>
<td>U</td>
<td>fixedValue (U, 0 0)</td>
<td>zeroGradient</td>
<td>fixedValue (0 0 0)</td>
</tr>
<tr>
<td>p</td>
<td>zeroGradient</td>
<td>Total pressure</td>
<td>zeroGradient</td>
</tr>
<tr>
<td>α (phase fraction)</td>
<td>FixedValue 1</td>
<td>OutletInlet</td>
<td></td>
</tr>
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Fig. 1. Film flow over triangular corrugation in a channel (a) 3-D simulation model (b) middle plane of the channel

The model is meshed by 600,000 structured elements, and the mesh has been refined several times until the results do not change. The real time in the model is 40 seconds and the system reaches steady state. The data in the middle plane of the simulated 3-D channel is interpolated to compare with the experiment results.
2.2. Introduction of the experiment system

The experiment system is displayed in Figure 2. Fluorescence tracer is chosen which is injected from a tiny hole in the bottom plate with a micro pump. The fluorescence tracer is illuminated by a UV light source and visualizes the streamlines close to the corrugations. The visualized flow field is photographed by a sCMOS camera (pco.edge).

![Figure 2: Sketch of experiment system](image)

Film flow in horizontal channel is investigated in the experiments. In most cases, the channel is partly filled and the film thickness is about 30mm. When the flow rate is increased to get a high Reynolds number, the channel is fully filled with liquid.

2.3. Comparison of simulations and experiments

To verify the 3-D simulations, experiments of film flow over triangular corrugations with different flow rates are conducted. The left column in Figure 3 shows the simulation results and the right column shows the corresponding from the experiments.

It can be found that when Reynolds number is small, no eddies formulated in troughs of the corrugations. When the flow rate is increased, different size of vertexes are formulated in different troughs. The eddy in the first trough is obviously bigger than the one in the second trough. The velocity in the first eddy is much bigger than the velocity in the second eddy, so the fluorescence tracer stays longer time in the second trough.
3. Numerical investigation of film flow over triangular corrugations

3.1. Remove of wall effect

For practical reason in the LIF experiments, a narrow channel with 5mm width is chosen to validate the simulations. But the side walls of this channel have effect on the flow that can not be neglected, which makes it difficult to focus on the effect from corrugations independently. To understand and take into account the wall effect, 3-D simulations of film flow in different width channels are carried out. The data on the middle plane (see figure 1) of these channels are interpolated to compare with the 2-D simulations. Figure 4 shows the sketch of 2-D model. OpenFOAM always generates geometries in 3-D by default, but the model will degrade to be a 2-D model by specifying a special ‘empty’ condition on the side walls. Then the program will not calculate the solution in z direction. The other boundaries have the same definition with those in 3-D simulations.
The error matrix is $M_{\text{error}} = [M_{\text{w,3d}} - M_{\text{2d}}]$, where $M_{\text{w,3d}}$ is a matrix composed by the velocity data on the middle plane of the 3-D simulated channel and $w$ is the width of the channel. $M_{\text{2d}}$ is the matrix composed by the velocity data from 2-D simulation. We used the norm of the error matrix $\|M_{\text{error}}\|_2$ to evaluate the difference between the 2-D simulation and the results from the middle plane of the 3-D simulations. It is shown in Figure 5 that when the channel is wider than 200mm, the flow field on the middle plane of the channel is very close to the 2-D simulation. This means the side walls have no effect on the middle plane of the channel when the width is wider enough and 2-D simulation can be applied to simulate the middle plane flow field.

3.2. Remove the effect from the starting and ending corrugation

The results of simulations and experiments indicate that flow field in the different troughs of the corrugations is different from each other. To find out the flow behavior in these troughs, flow over a substrate with eight triangular corrugations is simulated.

Figure 6 (a) shows that the eddy in the first trough is obviously different from other eddies. Figure 6 (b) and Figure 6 (c) shows the velocity profile in the middle of the troughs, from the bottom to the top. It is shown that the velocity profile in the first and seventh troughs are different from the others. The velocity profiles in the second to the sixth troughs are very similar and almost overlapped. The results reveal that when corrugations are more than four and troughs are more than three, the flow field in middle trough will not change anymore. In the following simulations, a model with five corrugations is chosen, and the flow field in the third trough is investigated.

It also can be found that the interface between liquid and gas is flat and no waves generate on the free surface. Streamlines in the region above corrugations are straight, so the corrugations on the bottom have little influence on this area. The mean velocity is increased because the channel becomes narrow here but the flow rate has to keep constant.
Fig. 6. Investigation of flow behavior over different length of corrugations (a) Streamline of the flow over eight triangular corrugations (b) x-component velocity profile in middle of the troughs (c) y-component velocity profile in middle of the troughs.
3.3. Investigation of steepness effect of the corrugations

We used 3-D simulation which is validated by experiments to investigate the wall effect and examine that wall effect can be removed by enlarging the width of the channel and 2-D simulation can be applied to simulate flow field in the middle plane of the channel. The effect from the starting and ending corrugation is investigated with 2-D simulations and proved to have no influence on flow in the troughs of middle corrugations. In the following study, effect of the shape of the corrugations on the flow field will be focused on and three types of corrugations with different steepness are studied. The triangular corrugations keep the same height (10mm) but different base angles (30°, 45°, 60°). The fluid properties are the same with the 3-D simulations and experiments.

Film flow over different shaped corrugations with different Reynolds numbers is discussed in the next step of this work. The results are displayed in Figure 7 and eddy size (area of the eddy) is measured from the simulated results. It is obvious that bigger steepness corrugations have stronger influence on the flow. Similar flow behavior which was found by A. Wierschm et al. [18] and M. Scholle et al. [21] in film flow over sinusoidal corrugations is also found in this study. In their investigations, eddies are induced in two ways. One type of eddies caused by corrugation steepness are named kinematically induced eddies, and the other type caused by inertia are named initially induced eddies. It is found that when the corrugations are steep (60°), eddies will always been formulated even the Reynolds number is reduced to close zero. These eddies are caused by geometry of the structure and the Reynolds number in this range has no influence on their formulation. For flow over corrugations with small steepness (30°), eddies are almost
Fig. 7. Streamline of the flow over corrugations with different steepness (a) Flow over corrugations with 30° base angles (b) Flow over corrugations with 45° base angles (c) Flow over corrugations with 60° base angles

eliminated when Reynolds number is low. But these eddies is enlarged dramatically with the increasing of Reynolds number, so they are initially induced eddies. Basically, flow over strong undulation corrugations is mainly dominated by the structure and changing the flow rate has little influence, vice versa.

Figure 8 (a) shows the area of the eddy verifies with the increasing of Reynolds number. Since the height of the corrugations is same, corrugations with different base angle have different hemline. To remove the length effect, area ratio (area of the eddy divided by corrugation section area) is induced. With the same height, the area of triangular corrugation section depends on the length of the hemline. So the area of the eddy divided by area of the corrugation section equates it is divided by the length of hemline. In this way, the corrugation substrate can considered to have the same length. Figure 8 (b) shows the variation of area ratio with increasing Reynolds number. It is interesting to find that every case has two variation regions. For film flow over corrugations with 45° steepness, the two regions are around Re<100 and Re>100. In the first region, the eddy size changes intensively when Reynolds number changes. In the second region, the trend becomes gently and the eddy size changes little. Basically, smaller steepness will delay the transition point and reduce the difference between these two regions.
In A. Wierschm et al. [18] and M. Scholle et al. [21]’s investigations, secondary eddies are found in the bottom of the trough when the undulation of the corrugations is strong enough. These secondary eddies are also found in this study. When the steepness of the corrugations is very big (60° for example), more eddies will be formulated on the bottom of the troughs.

3.4. Stagnant point movement when flow over arbitrary shaped corrugations

Formulation of eddies is always accompanied with stagnant point where flow is stagnated and the pressure reaches the maximum in this area. It is meaningful to investigate the stagnant point movement behavior, because it has significantly influence on transformation of flow field. To find out the principle of eddy formulation and investigate the relation between stagnant point movement and Reynolds number, film flow over arbitrary shaped corrugations is simulated. The first type of corrugation is shown in Figure 9(a). Big corrugation with 10mm height and small corrugation with 5mm height are alternately distributed. The second type of corrugation displayed in Figure 9(b) is hemicycle shaped with a radius of 10mm and a distance of 10mm between each other.

The simulation results displayed in Figure 9(a) indicate that the stagnant point moves up along the bottom of corrugation with increasing Reynolds number. When Reynolds number gets to 100~120, the stagnant point moves from one flank of small corrugation to the other and eddies on the both sides of small corrugation connects to each other. In Figure 9(b), it is found that the eddy formulated behind the corrugation is always much bigger than the one in front of the corrugation. With Reynolds number increasing, stagnate point is moving to right and the eddy behind corrugation is obviously enlarged but the one in front of the corrugation changes little. Keep the Reynolds number increasing, the two eddies connect and are united as one eddy.

3.5. Similitude analysis

As it is mentioned above, the size of the corrugations on structured plates in industrial equipments are often very small and the film thickness is less than 1mm, which causes difficulties in the measurement of the eddies in the trough of the corrugations. We choose relatively larger corrugations (with a height of
10mm) to get more precise results and to discuss the principle phenomena. This is based on the theory of fluid similarity. Reynolds number is often chosen to be a criterion to make sure the flow have similar behavior. But this is valid only in flow which is dominated by inertial and viscosity. Real model in industry is often more complex and influenced significantly by other factors. So it is necessary to simulate film flow over small corrugations and compare the results from the simulations above. The small corrugation that will be investigated is 1mm high but has the same base angle 45°. The material is same, so are the fluid properties. To keep the Reynolds number same \( \text{Re} = \frac{UL}{\nu} = \frac{U' L'}{\nu'} \), where \( U \) (\( U' \)) is the velocity, \( L \) (\( L' \)) is the characteristic length which is the film thickness in this case, \( \mu_w \) (\( \mu_w' \)) is the kinematic viscosity. \( L' = \frac{L}{10}, \mu_w = \mu_w' \), so \( U' = 10U \).

Film flow with the same Reynolds number, same material, over similar geometry but different scale corrugation is simulated and displayed in Figure 10. Obviously, the flow in these similar structures has very similar behavior. Figure 11 shows the relation between eddy formation and Reynolds number. To make the parameters dimensionless, area ratio is induced again. The results show that flow over different size corrugations has almost the same behavior, which proves that it is possible to apply the investigation on big model to predict the flow behaviour in small model.
4. Conclusion

Film flow over triangular corrugations is investigated by both simulations and experiments in this paper. To remove the surface tension effect and focus on the flow transition due to substrate on the bottom of flow field, flow with big thickness is chosen. 3-D simulation of film flow over triangular corrugations in a thin channel is carried out and validated by LIF (light induced fluorescence) method based experiments. Wall effect on flow in channels with different width is investigated with 3-D simulations. The wall effect can be eliminated when the channel is wide enough and the results in the middle plane of the channel are close to 2-D simulations.

Numerical investigation of film flow over corrugated substrate is conducted based on the analysis mentioned above. Film flow over three types of corrugations with different steepness is considered. We find eddies are caused in two different ways. One is caused by structure and has no direct relation to Reynolds number. The other is caused by the inertia force in the flow and Reynolds number has significantly influence on their formulation. Basically, the regime of flow over strong undulation substrate is dominated by structure geometry. On smooth substrates, Reynolds number has the primary effect on the flow regime. Another interesting phenomenon is that eddy formation in every case always
has two transition regions. In the first region, the size of eddy is enlarged dramatically with Reynolds number increasing. When Reynolds number reaches a critical value, the influence is reduced and the eddy size changes slowly. Smaller steepness will delay the transition point and reduce the difference between the two regions.

In the next step, film flow over arbitrary shaped corrugations is simulated. It is found that every eddy has a stagnant point behind it and the stagnant point moves when the Reynolds number increases.

The similarity theory in fluid dynamics is verified in this study. Similar flow behavior is found when the Reynolds number is kept same and geometry of the structure is similar. This proves that it is possible to apply the investigation on big model to predict the flow behavior on small structures.

Acknowledgements

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References


