Journal of Trends in the Development of Machinery and Associated Technology
Vol. 18, No. 1, 2014, ISSN 2303-4009 (online), p.p. 151-154

NUMERICAL AND EXPERIMENTAL INVESTIGATION OF LIQUID FILM MOTION ON AN INCLINED WALL

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ABSTRACT

This paper presents some of the results from numerical isothermal 3D computations as well as experimental measurements of the liquid film flow down an inclined solid wall. Computational fluid dynamics (CFD) simulation including a two-phase (water/air) volume-of-fluid model with free-surface, and visualization of the liquid film using a high-resolution camera are conducted. The film response for different entrance flow rates and different conditions at the film-side boundaries is examined. The flow properties and quantities of interests are liquid-film thickness, the shape of the liquid-film surface, and the surface-wave development. The simulation and experimental results are compared showing an acceptable agreement.

Keywords: liquid film, waves, free surface, fluid dynamics, simulation, CFD, visualization

1. INTRODUCTION

Liquid films arise in many technical applications where they may have a considerable impact on the process development and functionality of the facility components. They are important in industrial applications, such as absorbers, condensers, evaporators, chemical reactors and other related heat and mass transfer appliances [1-3]. For example, liquid films might induce additional thermal resistances in the heat transfer between the transported vapor and the pipe wall, their break-up might induce strong thermal stress variations leading to the material failure of the solid walls, or heat-loss triggered solidification of the liquid film, such as in slag, might increase the slag flow resistance or the weight of the structure. For proper treatment of liquid films in process plants, thorough understanding of their flow dynamics is of essential importance. The flow properties and quantities of interests are, among others, the shape of the liquid-film surface, liquid-film thickness, the surface velocity, and the surface wave behavior. Falling films and their detailed properties are described in [4,5]. Hydrodynamics of a falling liquid film is widely investigated experimentally [1–3,8]. In [6,7], variation of the dimensionless film thickness in terms of the Reynolds number is presented and compared with published data [8,9]. In addition to experiments, CFD provides possibility to investigate the local flow behavior of a liquid film. Two-dimensional simulation are carried out in [10–14], where 2D falling film flow on a vertical plane is simulated using finite-volume discretization with the VOF interface capturing method. This paper presents the results of 3D CFD simulations of the liquid film on an inclined plane, compared with the experiments.

2. NUMERICAL METHOD AND EXPERIMENTAL SETUP

Distilled water flowing down a solid plate sloped at a 45^{o} angle with respect to the horizontal plane is considered, see Fig. 1. The upper surface of the solid-plate, which is 500 mm long and 100 mm wide, is considered to be sufficiently smooth, due to its machining treatment. The water starts flowing from the top edge over the upper surface of the solid plate downwards. The side boundaries of the film in the experimental conditions are left free, but without overflow over the plate sides, while in the numerical calculations two different types of boundary conditions are applied at this place: symmetry plane ($v_n = 0, \partial v_t / \partial n = 0$), or wall ($v_n = v_t = 0$) boundary condition.

The solution domain for CFD simulations consists of a simple rectangular box, and the computational mesh is automatically generated using the Cartesian cells with subsequent refinement toward the wall surfaces, which is necessary in order to resolve the flow field variations caused by the wall effects.
The calculations emanate from the balance laws of continuum mechanics: conservation of mass and conservation of linear momentum. Since liquid film investigation implies the analysis of the liquid free-surface motion, an appropriate treatment is achieved by interface-capturing approach, which includes an additional equation for volume fraction of the liquid (water) phase inside the transporting (air) phase [15,16]. Turbulence effects (which may arise particularly in the region occupied by the air) are described by two additional transport equations for the turbulent kinetic energy and the dissipation rate following the *k-ε* model. The film flow is calculated using the commercial CFD software *STAR-CCM+*.
At the upstream boundary, the velocity of the two phases is specified, as calculated from the volume flow rate considered, see Table 1. The flow rate shown in the table is given for the plate width of 100 mm. The corresponding Reynolds number values are also listed; they are here defined as:

$$\mathrm{Re} = \frac{\rho v \delta}{\mu} = \frac{\rho \dot{V}_w}{\mu}\ , \tag{1}$$

where ρ is the density of the liquid, v is the characteristic velocity, δ is the film thickness, μ is the dynamic viscosity of the liquid, and $\dot{V}_w$ is the volume flow rate per unit of width. The downstream boundary is left open, to allow the outflow of the liquid phase.

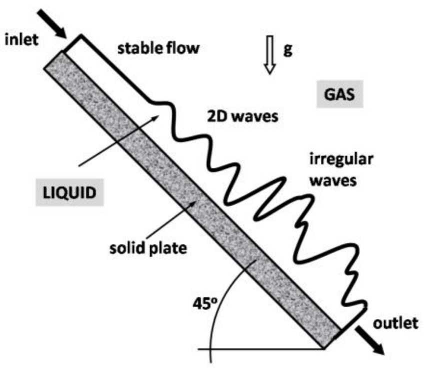

Figure 1. Liquid film flowing down an inclined solid plate.

Table 1. Inflow conditions of the liquid film used both in simulation and experiment.

Flow rate, l/h	Re
3.5	9.7
6.0	16.63
9	24.95
12	33.26

The average experimental conditions were as follows: liquid temperature was 22.8°C, air temperature was 23°C, and relative air humidity was 58 %. A high resolution camera (pco 1200s) with a spatial resolution of 1280x1024 pixels and the sampling rate of up to 500 fps was used. The camera was equipped with a zoom objective that has adjustable magnification. LED-backlighting of the liquid film was applied. The instantaneous film thickness is evaluated, whereupon its averaging is conducted for appropriate comparisons. The film thickness obtained from the camera images is analyzed with the software *Image J*, while the CFD calculation delivers the position of the water free surface as numerical data-sets directly.

3. RESULTS

Liquid films flowing down an inclined surface exhibit a transition along the solid wall: (i) from the flow with a stable, uniformly-shaped, almost “flat” free surface, (ii) over a flow dominantly characterized through development of two-dimensional waves, (iii) ending in three-dimensional waves of irregular shapes and sizes. Existing of these typical film flow structures has already been reported and documented by many authors [4,5], and are also found in the present experiments, as well as simulations, as illustrated in Fig. 2. Transition from a flat, stable flow in the upper part of the image, over nearly two-dimensional waves in the middle, to irregular surface shape in the lower part of the image is clearly seen. Also, in the case of the side wall boundary condition, narrowing of the film is noticeable, due to the boundary layers established along the side walls (Fig. 2 right). Certain deviation of wave patterns from the experiment and the simulation might be addressed to imperfection of reproduction of side-boundary condition and bottom surface roughness.

Typical averaged film thicknesses, as well as the characterstic wave dimensions obtained through the CFD simulations are given in Table 2, where the wave distance is calculated using FFT method.

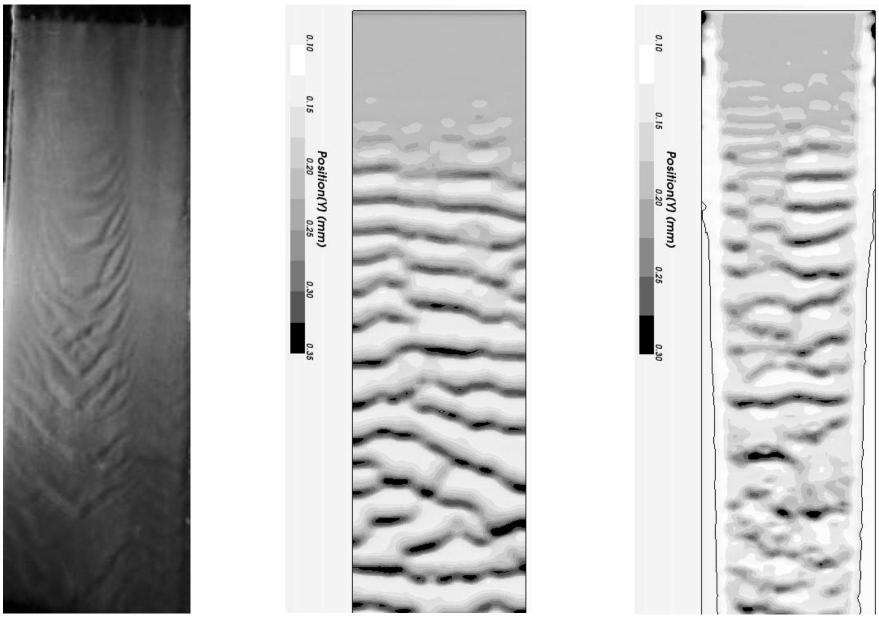

Figure 2. Shape of the free-surface of the liquid film, captured by a camera (left) and obtained from the CFD calculations with symmetry-plane boundary condition at the sides (middle), as well as with wall boundary condition at the sides (right).

Table 2.Predicted typical film dimensions in the irregular wavy region

Re	Mean film thickness, mm		Mean wave amplitudes, mm		Mean wave distance, mm	
	Symmetry plane b.c.	Wall b.c.	Symmetry plane b.c.	Wall b.c.	Symmetry plane b.c.	Wall b.c.
9.7	0.1465	0.1203	+0.1121 -0.0318	+0.0245 -0.0453	22.06	*
16.63	0.1479	0.1512	+0.1227 -0.0729	+0.1320 -0.0793	18.75	26.25
25	0.2040	0.1759	+0.1654 -0.0814	+0.1592 -0.1009	23.4	19.15
35	0.2264	0.2300	+0.2267 -0.0997	+0.2503 -0.1066	34.1	34.10

Dimensionless film thickness calculated as:

$$\delta^{+} = \delta_{\mathrm{mean}} \left(\frac{g \cos\varphi}{\nu^{2}} \right)^{1/3}, \qquad (2)$$

is depicted in Fig. 3 for a range of Reynolds-numbers, as obtained from the experiments and numerical calculations. The experimental results of other authors found in literature are also shown for comparison. The mean film thickness increases with the increase of the Reynolds number. While the results found by [8] seem to be relatively low, the other results are more or less clustered within a bandwitdh of 1, showing a similar trend of increase. The variation of the film thickness calculated with the wall boundary condition at the film sides is stronger than in the case of the symmetry boundary conditon. For lower Re-values, the film is thinner with the walls at the sides than with symmetry planes, becoming thicker for higher Re-values, indicating the trend of further increase. This is addressed to the effect of boundary layers developed from the wall side boundaries at higher Re-values, which make the effective cross-section of the flow narrower, leading thus to the increase of the thickness (see Fig. 2 right).

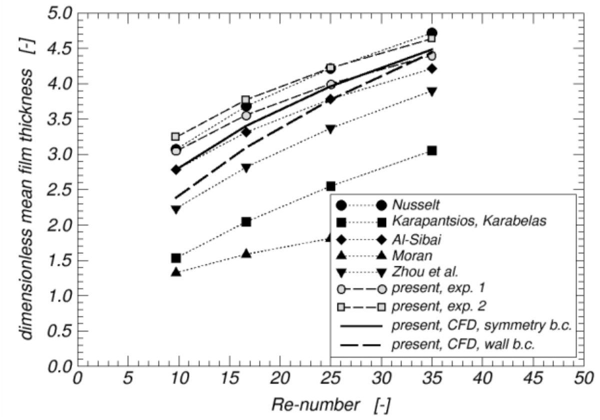

Figure 3. Dimensionless mean film thickness calculated using CFD and compared to experimental results from literature.

4. CONCLUSIONS

Both numerical and experimental results of liquid film visualisation are presented. Agreement of the measured and calculated film thickness is considered to be acceptable, and also agrees with some results published by other authors. While CFD approach offers detailed information on the local flow behaviour, it stills requires further investigation of modeling details such as side-boundary conditions as well as bottom plane roughness.

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