Characteristic of Falling Film on Inclined Plane Using FLUENT 12.0

By

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Dissertation submitted in partial fulfilment of the requirement for the

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CERTIFICATION OF APPROVAL

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Approved by,

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(Dr. Nurul Hasan)

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CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

MUHAMMAD SUAIDI B MANSOR

Abstract

Hydronamics of falling film has been studied widely to determine the characteristic of film on an inclined plate. When the computational model has not been used as main tool, researchers experimentally investigate the characteristic of falling film using numbers of technique, such as photochoromic dye activation technique and high speed video photography. Rapid developments in computational fluid dynamic enable researchers to investigate the characteristic of falling film through the simulation. In this simulation, the characteristic of falling film was studied over Reynolds number from 18-230. The results of velocity profiles and characteristic of falling film agreed reasonably with the Nusselt's (1916) prediction and Moran (2002) experiments.

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$u(y)$ = velocity profile

τ_w = wall sheer stress

δ = wall thicknes or film thickness

ρ = density

μ = viscosity

θ = angle of inclined plate from the verticle

g = Gravity acceleration

u_{mean} = Mean film velocity

u_{max} = maximum film velocity

σ = Surface tension

w = width of the plate

u_x = velocity of the fluid at x position

v = kinematic viscosity

G = Mass Flow Rate

Re = Reynolds Number

γ = Kapitza Number

List of Equation

$$u(y)=\frac{\rho g\delta^2\cos\theta}{2\mu}\left[\frac{2y}{\delta}-\left(\frac{y}{\delta}\right)^2\right]$$ **1**

$$\tau_w=\rho g\delta\cos\theta$$ **2**

$$\delta=\left[\frac{3\mu U_m}{\rho g\cos\theta}\right]^{0.5}$$ **3**

$$(\delta-y)wdx\rho g\sin\theta$$ **4**

$$\mu\frac{du_x}{dy}wdx$$ **5**

$$(\delta-y)wdx\rho g\sin\theta=\mu\frac{du_x}{dy}wdx$$ **6**

$$\int_0^{u_x}du_x=\frac{\rho g\sin\theta}{\mu}\int_0^y(\delta-y)dy$$ **7**

$$u_x=\frac{\rho g\sin\theta}{\mu}(\delta y-\frac{1}{2}y^2)$$ **8**

$$G=\int_0^s(\frac{\rho g\sin\theta}{\mu}\left(\delta y-\frac{1}{2}y^2\right))\rho dy$$ **9**

$$=\rho^2g\frac{\sin\theta}{\mu}w(\frac{\delta^3}{2}-\frac{\delta^3}{6})$$ **10**

$$=\rho^2g\frac{\sin\theta}{3\mu}w\delta^3$$ **11**

$$u_{mean}=\frac{\rho g\sin\theta\delta^2}{3\mu}$$ **12**

$$u_{\max}=\frac{\rho g\sin\theta\delta^2}{2\mu}$$ **13**

$$\delta=a(\frac{v^2}{gcos\theta})^{1/3}\mathrm{Re}^b$$ **14**

$$\mathrm{Re}=4u_{mean}\delta/v$$ **15**

$$u=a(gcos\theta/v)\delta^2$$ **16**

$$\frac{u_{\max}}{u_{mean}} = \frac{3}{2} \qquad \textbf{17}$$

$$\gamma = \sigma / \rho v^{4/3} g^{1/3} \qquad \textbf{18}$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \qquad \textbf{19}$$

$$\rho\left(\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}\right) = -\frac{\partial p}{\partial x} + \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) + F_{stx} + mg_x \qquad \textbf{20}$$

$$\rho\left(\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y}\right) = -\frac{\partial p}{\partial y} + \mu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) + F_{sty} + mg_y \qquad \textbf{21}$$

CHAPTER 1

INTRODUCTION

1.1 Background of Study

The hydronamics of liquid film is important at condition where it is on inclined, horizontally or vertically in many of industrial application. The influence of gravitational force must always be taken into consideration as it will give impact to the flow of the liquid. In industrial application the falling film may exist in the wetting wall absorbers, condensers, vertical tube evaporators and falling film chemical reactors. All of these equipment was designed after taken consideration of many aspect such as the rates of heat transport, the type of fluids that involved and also the material of the equipments itself. In many studies, the mass transport process for wavy falling films are significantly affected by the characteristics of the falling film such as the thickness, velocity distribution, and wall sheer stress variations. The wide range of Reynolds number has also been said to be one the affecting criteria but it is not well been understood by researchers, Moran (2001).

The hydrodynamic characteristic has been studied widely in the past, however due to the thickness of the film is very small and frequently came out as unit of millimeter (mm), the researchers found the difficulty to the measurement of the local flow structures.

The techniques that past researches used to measure the velocity profiles in falling liquid films includes the ultramicroscope techniques, stereoscopic photography, volumetric hold-up and laser Doppler anemometry Moran (2001). According to Moran (2001), Grimley (1945) reported the significant deviations of the measured velocity profiles in wavy water films from the parabolic profiles predicted by Nusselt

(1916). However, there are several researcher reported good agreement with the parabolic distribution of velocity profile for water as calculated by Nusselt (1916).

Experiment is rather difficult to measure the velocity of the falling liquid film due the thickness of the film that is small. Nakoryakov (1977) as concludes by Moran (2001), used stroboscopic visualization of spherical aluminum particles in water glycerines-film to measure the velocity profiles together with a shadow graph method to determine the instantaneous film thickness and later on extended by Alekseenko (1985) stated that at Re=50 the velocity profiles under interfacial waves are well behaved and conform to a parabolic profile with little fluctuations.

Moran (2001) stated that, Brauer (1956) measured the wall sheer stress in falling liquid films at verticle tube and Fulford (1964) measured it on an inclined plane. Study by Fulford (1964) indicates that the wall sheer stress was greater than the classical prediction made by Nusselt (1916). Wasden and Dukler (1989) measured the shear stress in vertical annular falling film and indicate that wall sheer stress achieved peak values in the wave front regions. The finding was supported by Lyu and Mudawar (1991). In the electrochemical techniques perform by Aragaki (1990), the wall sheer stress value calculated from the study agrees with the Nusselt's (1916) theory of wall sheer stress.

1.2 Problem Statement

Before the development of simulation software, researchers investigate the characteristic of falling film by numerical study and experiment. However, the theory and result from the experiment may not be accurate as the transport phenomena analysis is difficult to be seen experimentally. As from Moran (1997), characteristic of falling film falling on inclined plane is compare with Nusselt (1916) data. When the simulation software has been introduced, the simulation of falling film has been investigated widely by some researchers like Z.F Xu (2008). Therefore from the journal by Moran (2001), the study of falling film on inclined plane was performed in this project by using simulation software.

1.3 Objectives

Most of the journals cited experimentally study the characteristic of the falling film. However nowadays, there are computational software that can be used to study the characteristic of the falling film on an inclined plane. Software like FLUENT and also TRANSAT are the example of the computational fluid dynamic (CFD) software that can be used to investigate the fluids characteristic. The purpose of this project is to obtain the velocity profile and wall sheer stress data in a viscous film flowing on an inclined plane.

1.4 Scope of study

For the purpose of this project, the study will focus on the study of characteristic of falling film on an inclined plane. The characteristic of falling film will be different for different of Reynolds number, the degree of inclination and also type of the fluid. In this project the fluid that will be used for the study is Silicon Fluid 200 which the properties of the fluid are shown on Table 2.2.1. The simulation will use FLUENT 12.0 to generate the result.

CHAPTER 2

LITERATURE REVIEW

Nusselt (1916) theoretically analyzed the falling liquid film with the assumption of steady rectilinear with smooth and sheer-free gas liquid interface. Nusselt came out and developed the equation number (1), (2), and (3).

2.1 Computational Model

In transport phenomena analysis, there's a mathematical model to calculate the velocity profile of fluid on an inclined plane. Some book may give different formulation but at the end the understanding of velocity profile is just same for all. As for this project, Numerical analysis has been studied from Coulson & Richardson (1999).

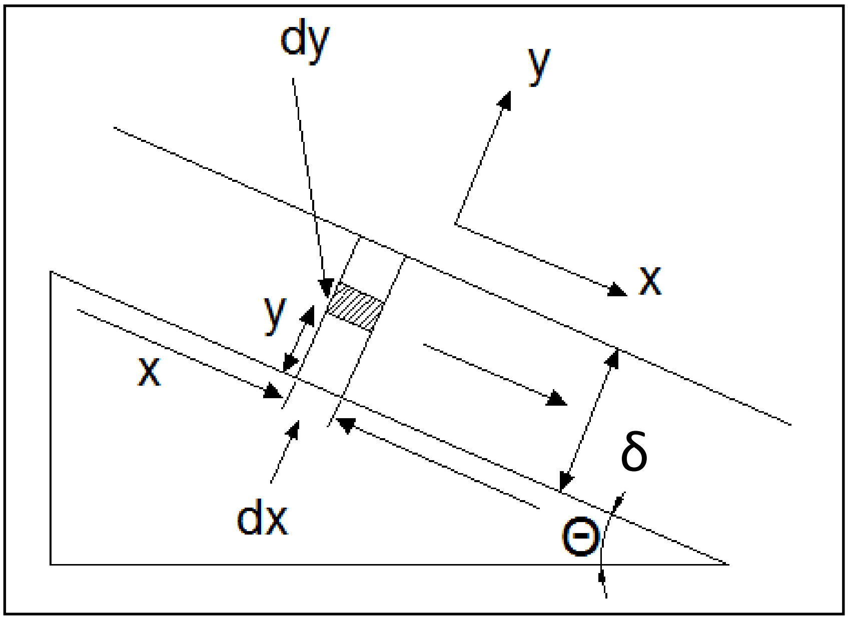

Figure 2.1: Flow of a liquid over a surface

For the flow of liquid over a surface at inclined plane, the Figure 2.1 represents the details for the computational of the velocity profile.

In an element of length dx, the gravitational force acting on that part of the liquid which is at a distance greater than y from the surface is given by the equation(4)

If the drag force of the atmosphere is negligible, then the retarding force for laminar flow is attributable to the viscous drag in the liquid at the distance ‘y’ from the surface given by equation (5), Since there will normally be no slip between the liquid and the surface, then ‘u_x’ equal to zero when ‘y’ equal to zero, and will generate equation (7).

The mass rate of flow of liquid down the surface is now calculated using equation (9) and simplify to equation (10) and (11). The mean velocity of the fluid is given by equation (12). The maximum velocity, which occurs at the free surface, is given by the equation (13)

Relation between film thickness and the Reynolds number is given by equation (14). Relation between Reynolds number and the mean velocity is given by equation (15). Relation between velocity and the film thickness is given by equation (16). Relation between maximum velocity with the mean velocity is given by equation (17).

Most of the equations were found from Moran (2001), however for equation (4) to (13), it was obtained from Coulson & Richardson (1999). The equation will be used to analyze the results from simulation for validation with Nussselt (1916) and Moran (2001).

2.2 Experimental Setup

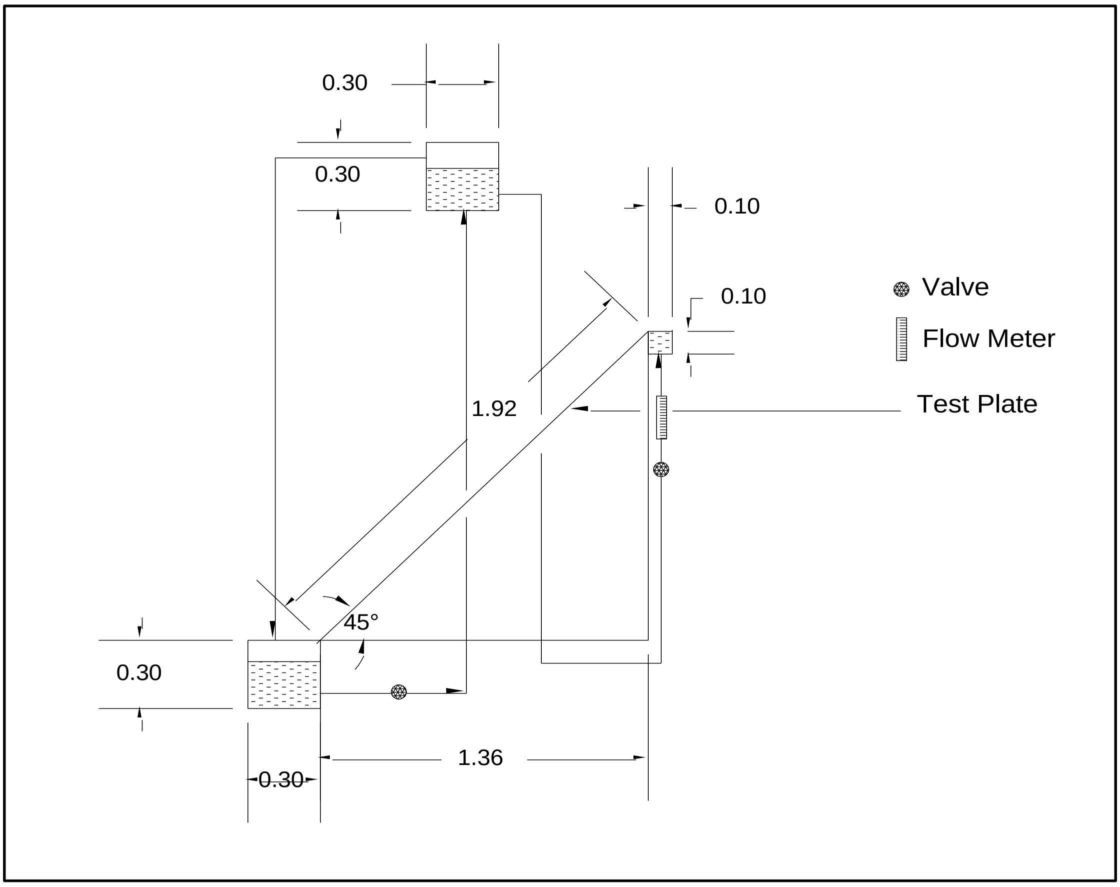

Figure 2.2.1: Experimental setup by Moran (2001)

In Moran's (2001) study, the experimental setup was done as shown in Figure 2.2.1. The dimension of the test plate is 1.92 m long and 80 mm wide. The test plate is smooth to ensure there is no disturbance of the fluid while it is flowing down on the inclined plane. The plane is inclined on 45^0 from the vertical. The side of the plate is covered with the polycarbonate transparent material to enable viewing of the longitudinal cross section of the film. The entrance of the surface was smoothly rounded to ensure fair distribution of the flow to the entire width of the plate.

The design of the Moran (2001) used the gravity driven force for the fluid to flow. With the help of control valve and the flow meter, the speed of liquid flow into the tank can be control at maximum rate of 6.2 LPM. The dimension of the tank 1 is not clearly indicate by Moran in the paper, however, as mentioned from the paper, the total test section was said to be 2.27 m which can be assumed that the tank that held fluid down on inclined plane is rectangular box with 0.35 m in dimension.

The working fluid used by Moran in his study was Silicon Fluid 200, manufactured by Dow Cornings. The properties of the fluid at temperature of 22^0C can be described as follows.

Table 2.2.1: Properties of fluid by Moran (2001)

Kinematic Viscosity (m^2/s)	$2x10^{-5}$
Density (kg/m^3)	$9.6x10^2$
Surface tension (N/m)	$2.06x10^{-2}$
Dynamic viscosity (kg/m.s)	$1.92x10^{-2}$

2.3 Theory

From Moran (2001), the thickness of the fluid is calculated since Moran experimentally investigates the characteristic of falling film. From the paper, the relation of film thickness with the Reynolds number is given by equation (14). The Re number can be calculated by equation (15)

Nusselt (1916) predicted that the constants to be a = 0.909 and b= 1/3 for the Silicon 200 flowing over flat plate with 45° of inclination from vertical surface, meanwhile Moran found that the value of a = 0.97 and value of b = 1/3. Moran (2001) strongly agreed with the results since other researcher which are Takahama and Kato (1980) present similar result with him.

Another characteristic of falling film that has been studied is the mean and maximum velocities. Nusselt (1916) proposed that the relation between time averaged mean and maximum velocities with the film thickness is given by equation (16) where constant ‘a’ equal to 1/3 for the mean velocity and ½ for the maximum velocity. Moran (2001) found that the value of constant ‘a’ for mean velocity is 0.29 and for maximum velocity is 0.44.

Nusselt (1916) stated that the ratio of maximum to mean velocity in the laminar film is given by equation (17). Prediction by Nusselt (1916) has been supported by Coulson & Richardson in the book where the equation for u_{mean} is given by equation (12) and u_{max} is given by equation (13). When the ratio of maximum velocity to the mean velocity is calculated based on the equation, the result will give the ratio of 3/2.

From Moran (2001), the ratio of maximum velocity to the mean velocity obtained is equal to 1.47 which is slightly lower than the prediction of Nusselt (1916). Other researchers also experienced lower ratio where Portalski (1964) obtained the ratio of 1.4, however, Koziol (1981) obtained larger ratio which is 1.8.

Moran (2001) stated that for the instantaneous maximum to mean velocity ratio was found to fluctuate around the mean value for all Reynolds numbers but the amplitude of fluctuations did not change significantly over the Reynolds number examined. Moran (2001) simply conclude that for the laminar flow the instantaneous maximum to the mean velocity profile follow the Nusselt's (1916) theory with a little fluctuations around the prediction value.

From this findings, it shows that not only Reynolds number affecting the velocity profile of the falling film. Kapitza number was said to have a correlation with the velocity profile. From Moran (2001), the kapitza number is dimensionless parameter which can be identified by the equation (18). However the effect of Kapitza number is not been studied by Moran (2001) due to insufficient amount of data and it is difficult to conclude the dependence of Kapitza number with the velocity profile.

The instantaneous velocity profile was calculated by Moran (2001) in his experiments where he observed that the instantaneous velocity profile in the smooth film region followed Nusselt's (1916) prediction with deviation of less than 10%. Moran (2001) concluded that for the experimental result, the time average film thickness data were slightly under predicted by Nusselt's theory while the mean velocity profiles were over predicted by Nusselt(1916) prediction.

Chapter 3

METHODOLOGY

Methodology refers to methods/procedure used to achieve the objective(s) of the project. In this project, certain software has been used to achive the simulation.

3.1 Meshing

The first software that has been used to draw the mesh of the simulation is GAMBIT 2.4. The purpose of meshing is to enable the simulation iterate for the volume of fraction method. In this research fine mesh has been design with the size up to $7x10^5$. The fine mesh produces fine result however it will takes longer time to complete the simulations. The Fine mesh then converted to FLUENT 12.0 to run the simulation.

The mesh domain has been draw using Moran (2001) figures.

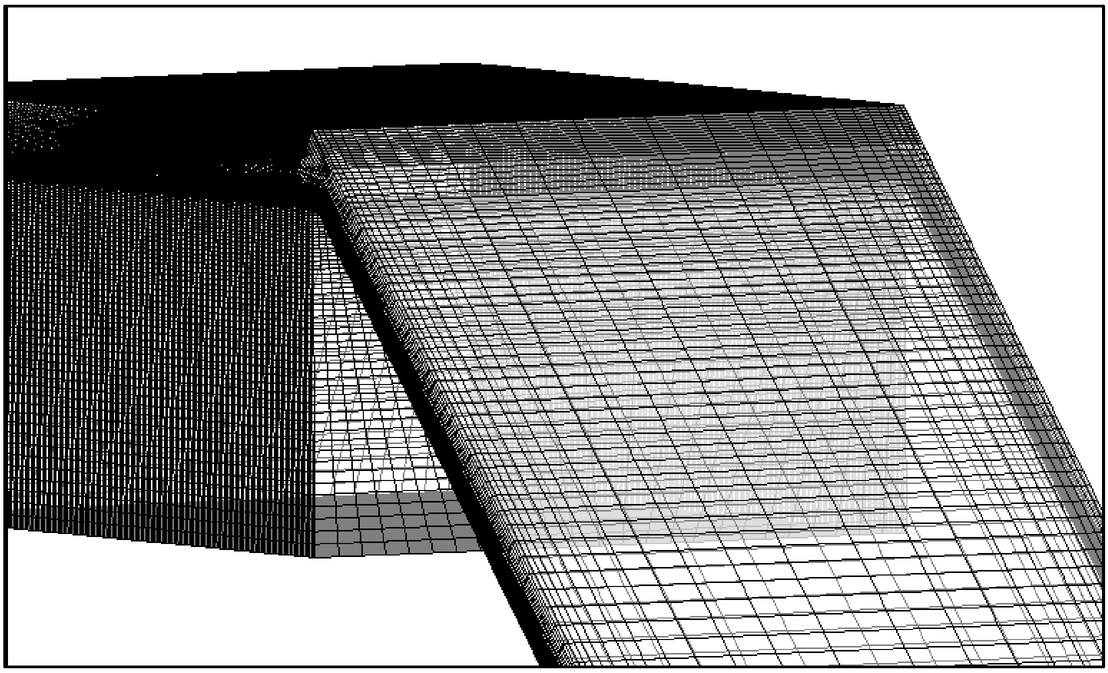

Figure 3.1: Mesh of the simulation

The dimension of the tank is 10 cm long x 10 cm height x 80 mm wide. The test section plate is 1.92 m long. From this mesh, the simulation then has been carried out using FLUENT 12.0.

3.2 Simulation Set Up

Table 3.1: Computational parameters for the inclined plane film of fluid Silicon 200

Computational Parameters	**Setting of the Computational Parameters**
Mesh Type	Quadrilateral
Solver	Unsteady
Discretization	Pressure(body force weighted), momentum(second order upwind),volume fraction (modified HRIC)
Pressure-velocity coupling	PISO
VOF parameters	Geometric reconstruction
Wall of the inclined plane	Smooth (K_s =0 and C_s =0.50)
Time Step	0.001 sec

In the simulation using FLUENT 12.0, courant number sometimes gives problem therefore has interrupt the simulation. The time step then was adjusted to be variable where it will varies according to the courant number.

The model that has been used in this research is the Volume of Fluid (VOF) with the geometric reconstruction as the parameters. VOF is a method to predict the flow n open channel and free surface. In VOF model the important equation that has been included in the model is the continuity and momentum equation (19), (20), and (21) below.

3.3 Assumptions

The assumption for this research is that the fluid is flowing down with unsteady state laminar with the smooth surface of the plate. The fluid will not change its properties at 20 degree Celsius and the gravitational force remains constant at all time. These assumptions have to be made so that the result of the simulation can be compared to the experimental data by Moran (2001). Another important assumption is that the effect of waves is not been studied in this project.

Table 3.2: Gantt chart

No	Detail/Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	Project Work							Mid Semester break													
2	Submission Progress Report 1																				
3	Submission of Progress Report 2																				
4	Poster/Pre-EDX																				
5	EDX																				
6	Submission of Final Report (CD & Softbound)																				
7	Final Oral Presentation																				
8	Submission of Hardbound Copies																				

Chapter 4

RESULTS AND DISCUSSION

4.1 Data Gathering and Analysis

Table 4.1.1: Simulation data for characteristic of falling film at inclination of 45 degree

Case	Flow rate (kg/s)	Film thickness(mm)	Mean Velocity (m/s)	Maximum Velocity (m/s)	Reynolds number	Shear Stress (Pa)
Case 1	5.33E-03	7.64E-01	1.24E-01	1.83E-01	1.80E+01	5.27E+00
Case 2	7.62E-03	8.53E-01	1.59E-01	2.36E-01	2.70E+01	6.07E+00
Case 3	8.77E-03	9.32E-01	1.98E-01	3.05E-01	4.00E+01	6.86E+00
Case 4	2.75E-02	1.77E+00	3.59E-01	5.13E-01	1.27E+02	9.82E+00
Case 5	6.43E-02	2.27E+00	5.07E-01	7.61E-01	2.30E+02	1.47E+01

From Table 4.2, the simulation data was converted to the CGNS file to further analyzed using TECPLOT 360 software. From TECPLOT 360, the film thickness was measured. The mean velocity and maximum velocity was measured using FLUENT 12.0. Same goes to the Shear Stress wall where in the FLUENT 12.0 it will show all the characteristic of falling film needed for this project.

4.2 Results and Discussions

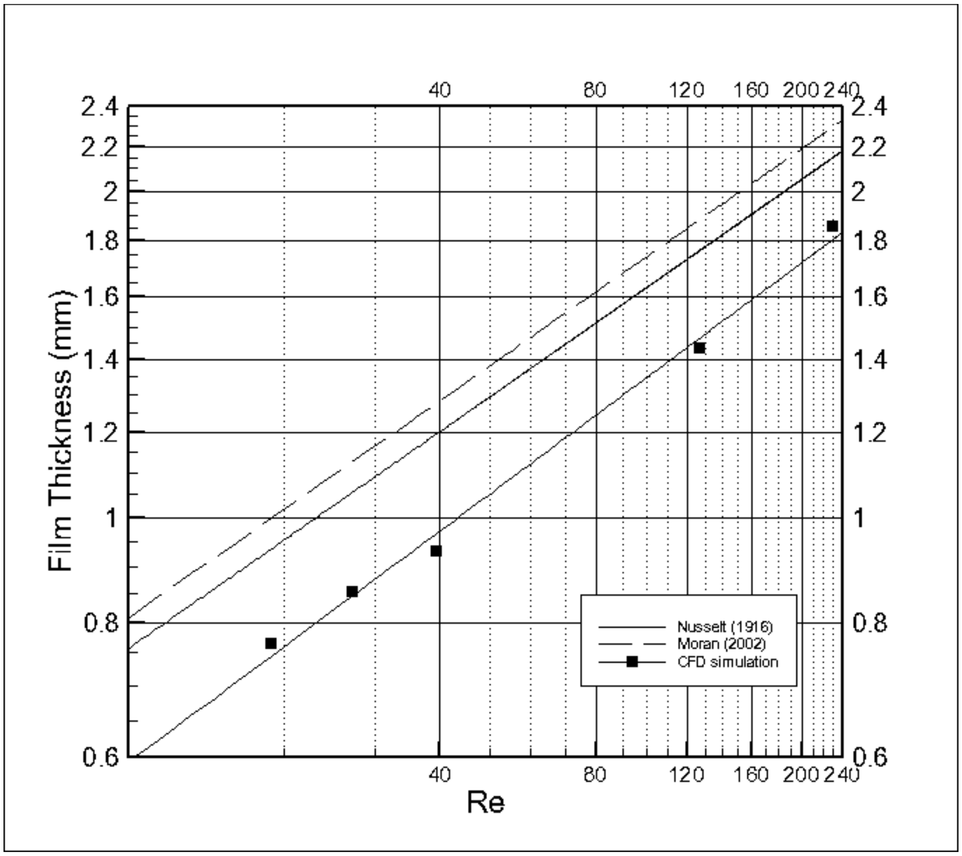

Figure 4.2.1: Variation of film thickness and Reynolds number

The film thickness increases with Reynolds number as shown in figure 4.2.1 which follows the trend proposed by Nusselt (1916). The relationship between film thickness and Reynolds number is given by equation (14).

Nusselt (1916) predicted that the value of a = 0.909 while the value of b = 1/3. Moran (2001) in his experiment data obtained the value of a = 0.97 and b= 1/3 for silicon fluid flows at inclination of 45 degrees. However in this CFD simulation the value of a = 0.64 while value of b = 0.3 which has a small variation compared to Moran (2001).

Even thought the difference may be very small, Moran (2001) explains that the effect of film thickness discrepancy on the film flow rate prediction can be quite large because the liquid velocity is the largest in the interface region.

Furthermore some of the authors have reported the same prediction and the results were similar to the Moran (2001). It is clear that the Nusselt (1916) prediction can be used as a source of reference for the researchers to find clue and validate experimental data with the CFD simulation.

When Reynolds number increase, the thickness of the film also increase as shown from figure 4.2.1. Reynolds number influences the hydronamics of falling film because Reynolds number determines the condition of fluid flow which either laminar or turbulent. When Reynolds number is less than 2300, the flow is considered laminar while when the Reynolds number more than 4000 the flow is considered turbulent.

In Transport phenomena and fluid dynamics, Reynolds number is very important aspect as it will give influence to the flow of fluid. As in this CFD simulation the type of fluid that has been used is Silicon 200 which has the dynamic viscosity of 0.0192 kg/m.s. Viscosity as stated in Moran (2001) also influences the characteristic of falling film. Viscous fluid tends to flow slowly and therefore according to the equation (22) when the viscosity is large the Reynolds number will be small according to this equation hence the flow becomes steady.

Even though in Moran (2001) did not explain the relationship between viscosity of the fluid and the Reynolds number, from the equation that has been found it is clearly shown that increasing in the viscosity of the fluid will decrease the Reynolds number, hence, give more laminar characteristic to the fluid.

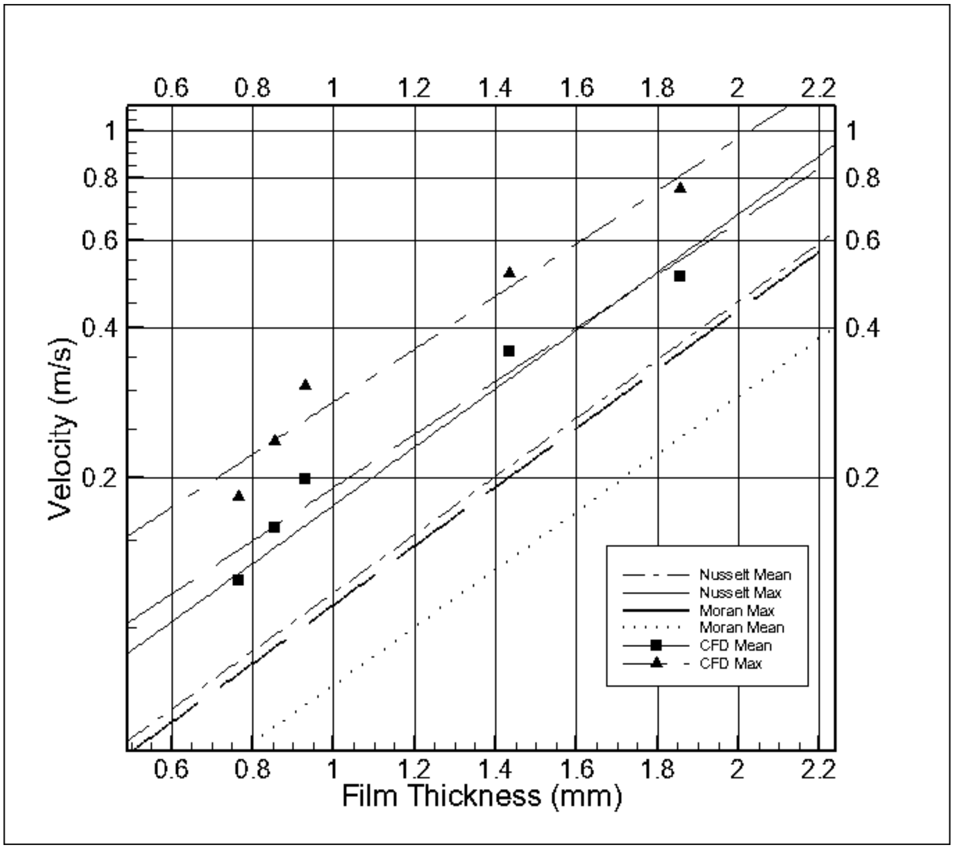

Figure 4.2.2: Comparison of mean and maximum velocities

In Figure 4.2.2, the mean and maximum velocities have been plotted against the thickness of the film for all the five cases and have been compared to the Nusselt (1916) prediction and also experiment data of Moran (2001)

From equation (16), Nusselt (1916) predict the value of a = 1/3 for mean velocity while 1/2 for maximum velocity. Summary of constant a for Moran (2001) Nusselt (1916) and in this CFD simulation is given as Table 4.2.

Table 4.2.3: Comparison between constant **a**

	Constant **a** value	
	Mean velocity	Maximum velocity
Nusselt (1916)	1/3	½
Moran (2002)	0.29	0.44
CFD Simulation	0.307	0.4496

Based on this value the CFD simulation and Moran (2001) constant seem to show a negative deviation compared to the Nusselt (1916). For comparison with the Nusselt (1916) constant, the deviation for CFD simulation is 7.9% for mean velocity and 10% for maximum velocity. It is good result since the error is below 20%.

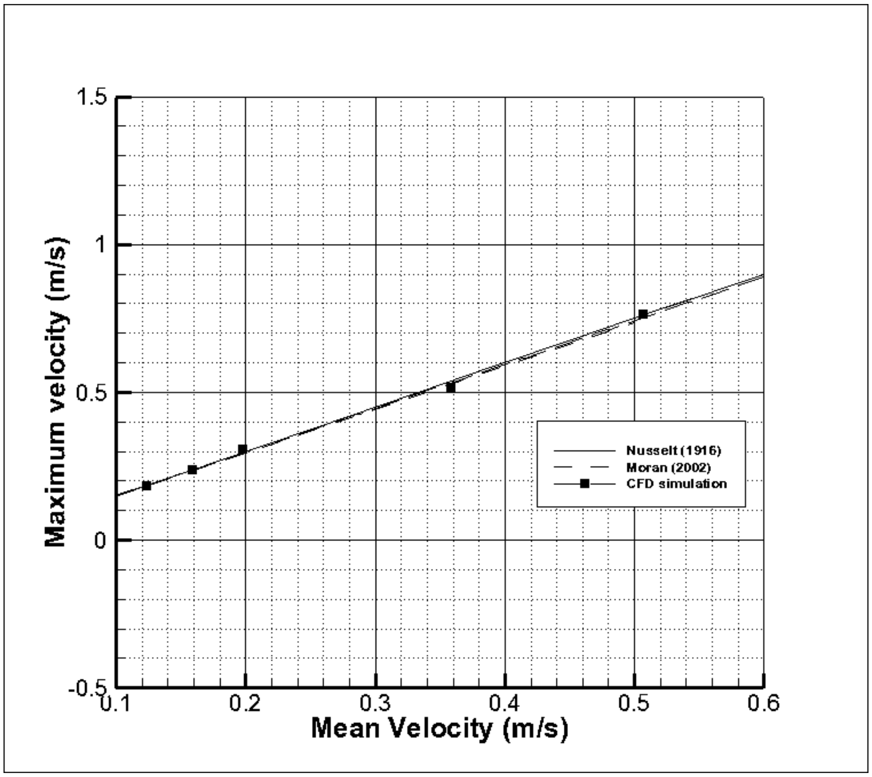

Figure 4.2.4: Comparison of mean and maximum velocities.

According to Nusselt (1916), the ratio of the mean velocity to the maximum velocity is given by the ratio of 1.5. In this CFD simulation the ratio that has been calculated is 1.48 slightly lower than Nusselt (1916) ratio and almost same to Moran (2001) ratio which is 1.47. Moran (2001) identify that the ratio of the mean to maximum velocity increase with the increasing of the Kapitza number.

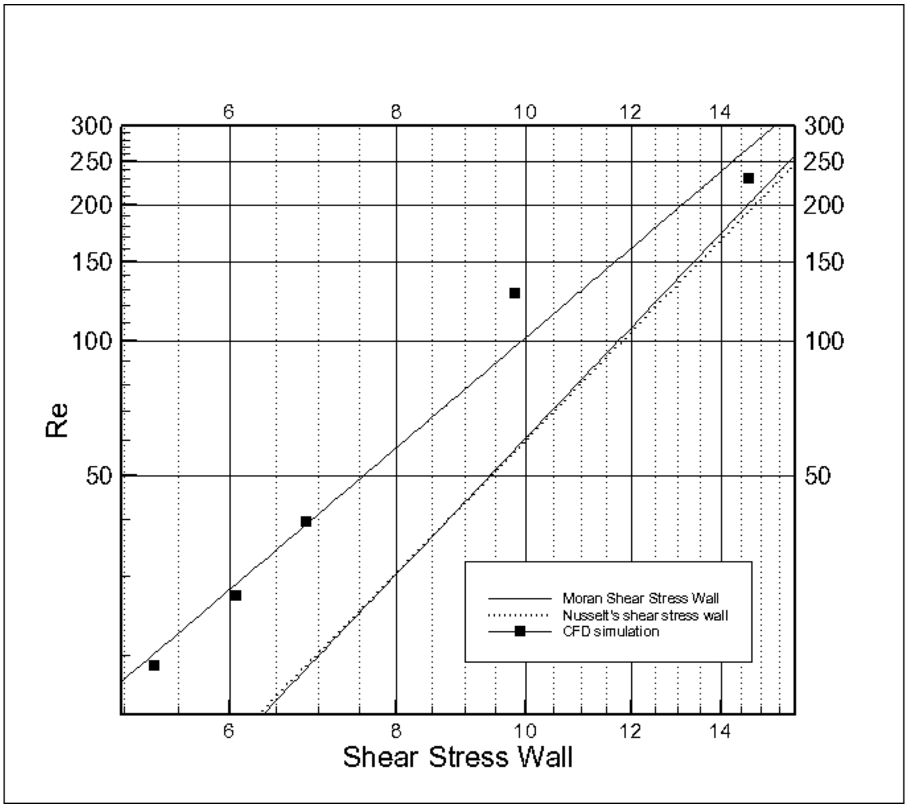

Figure 4.2.5: relationship between Reynolds number and sheer stress wall

Wall sheer stress was obtained In FLUENT 12.0. As reported by Moran (2001), the wall sheer stress will increase as the Reynolds number increases and this is agreed with the Nusselt's (1916) prediction. The deviation of the wall shear stress occurs in this CFD simulation because the effect of wave has been negligible during the simulation. However the trend in Figure 4.2.5 shows good agreement with Nusselt (1916) and Moran (2001).

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

The characteristic of falling film on an inclined plane has been studied using simulation software. The data obtained has agreed with Moran (2001) data and even though the data have a little deviation compared to Nusselt (1916) data it concluded that the simulation has shown good result in predicting the characteristic of falling film on inclined plane for Reynolds number ranging from 18-230. The study is acceptable and the use of simulation in industry application is important so that engineers can understand the effect of fluid dynamics before apply it to the real situation.

5.2 RECCOMENDATION

In order to produce more accurate result the effect of wave has to be include in the simulation. The frequency of moving liquid can varies with the time hence it will give impact to the velocity profile of the liquid film. From the fluent simulation, the User Defined Function (UDF) enables researchers to create a function for the simulation. The function that can be edited with C++ programming will adapt with the simulation and improve the result of the simulation. The effect of Kapitza number from the equation (18) can also be included in the simulation, as from the simulation the effect of kapitza number has been negligible. For the future study, the effect of Kapitza number can be included together with the Reynolds number effect so that the accuracy of the results increased hence reduced the error.

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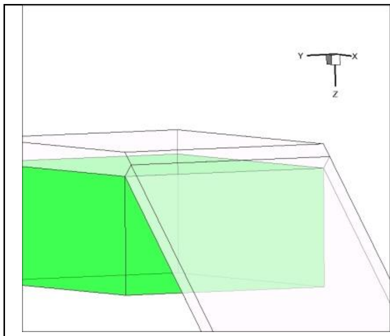
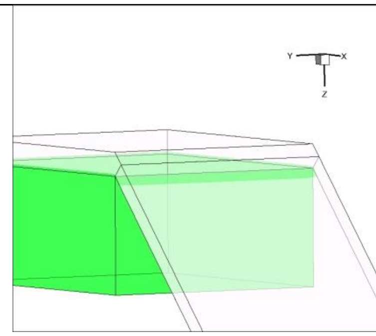
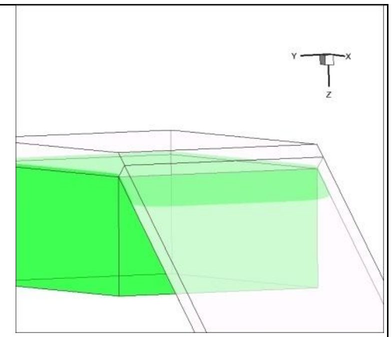
APPENDICES

Animation for case 2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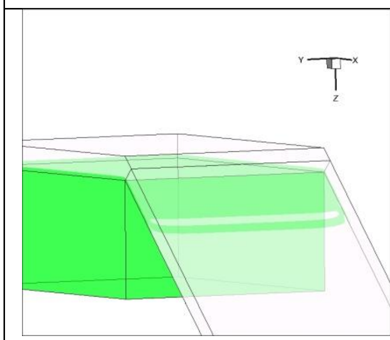	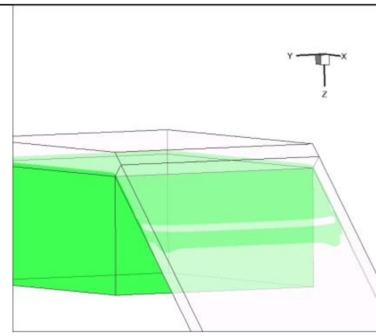	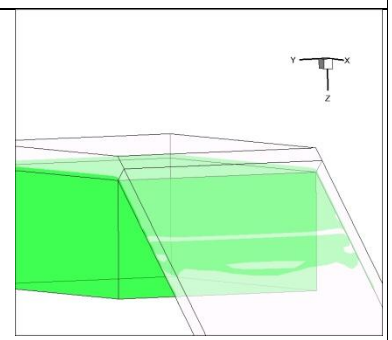
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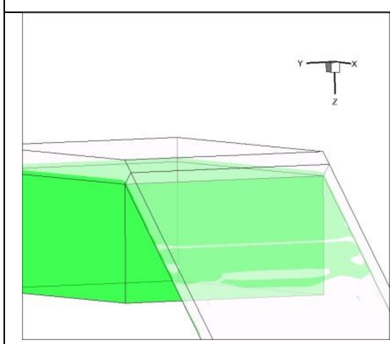	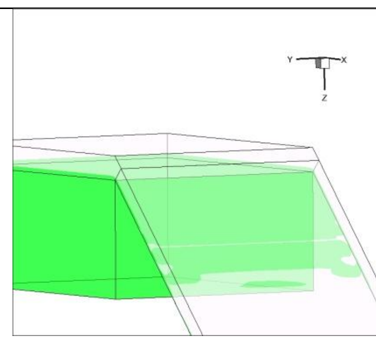	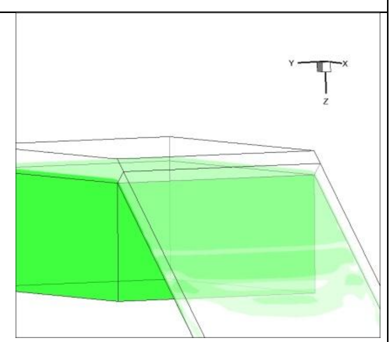
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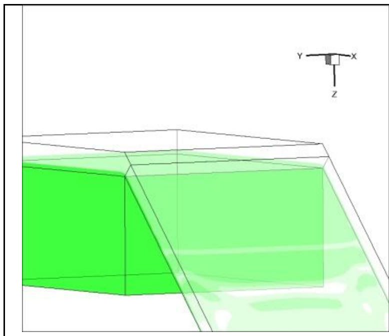	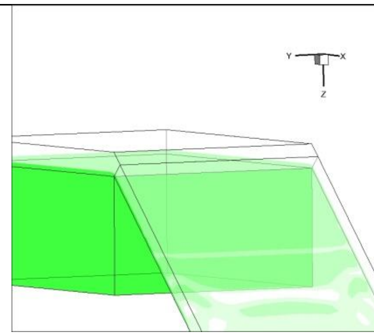	
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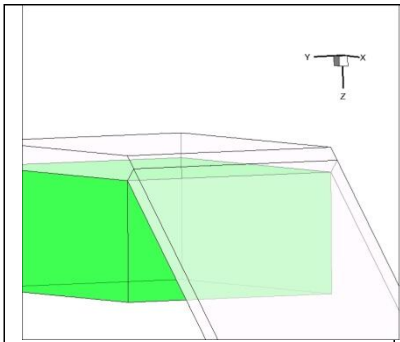
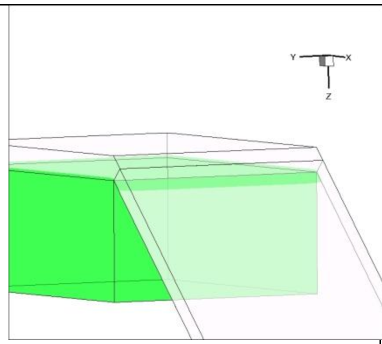
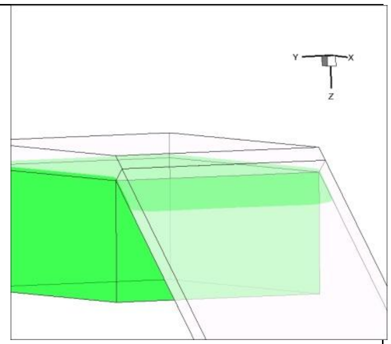
Animation for case 3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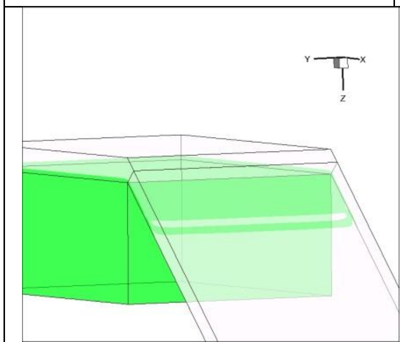	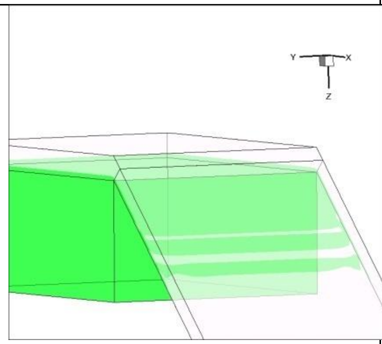	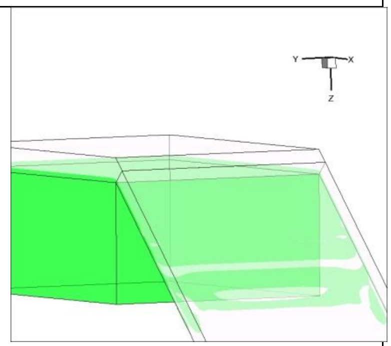
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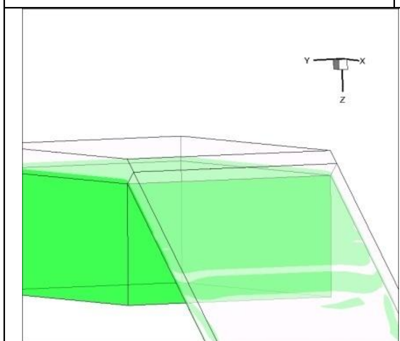	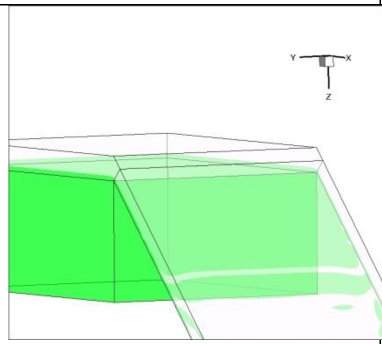	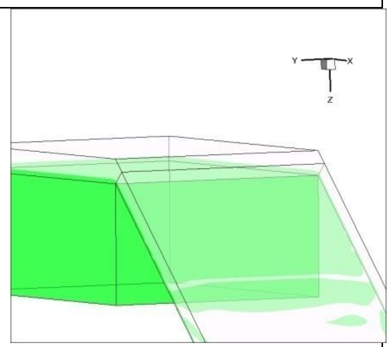
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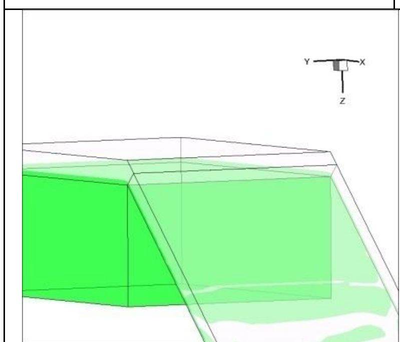	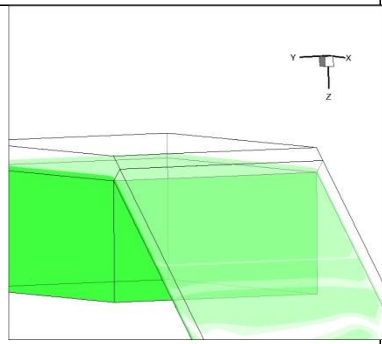	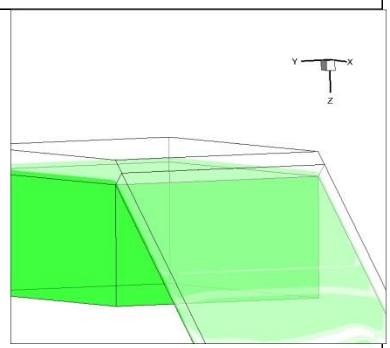
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Velocity profile for case 2

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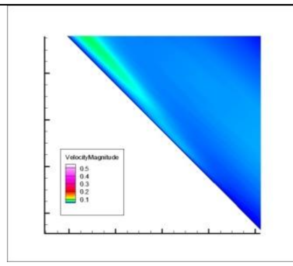
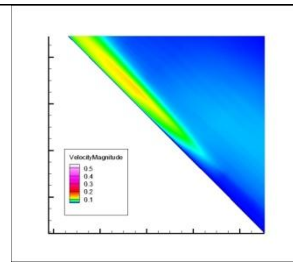
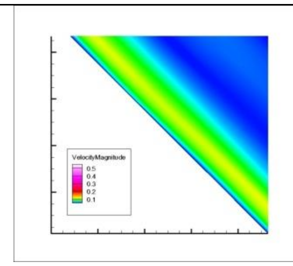
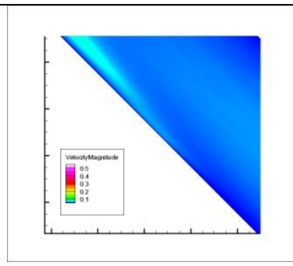
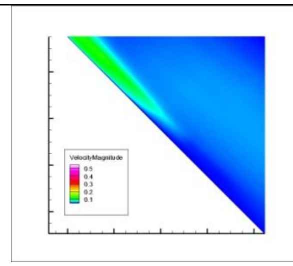
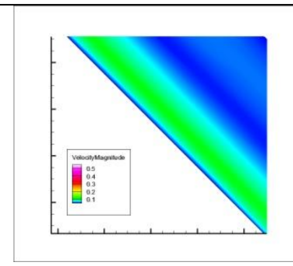
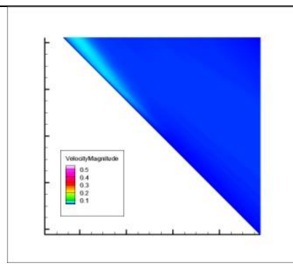
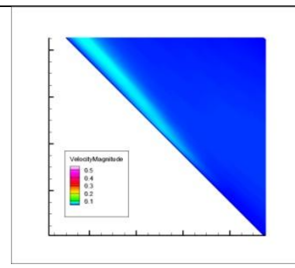
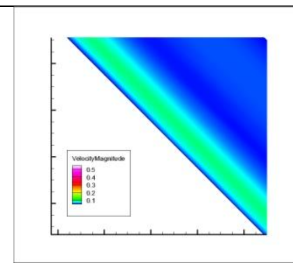
Middle of the plane (50%)			
25%			
Side of the plane			
Contour of velocity magnitude (m/s)