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MASTER'S THESIS

TITLE: TRANSIENT FLOW ANALYSIS OF HINGED DOOR	SUBMISSION DATE: 09.06.20021
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ABSTRACT:

The purpose of this thesis is to analyze the movement of hinged door by using CFD simulation software. This work is very to the present pandemic situation because it analyses the movement of mass between to rooms. Transient flow analysis is used due to the variations of flow properties with time and space. In this case, mass flow, air velocities, transfer of energy in the form momentum and movement of pollutant is analyzed from the result of the simulation. In the simulation to regions is created one for the overset (door) and the other for the domain (air). The movement of the door which gives rise to air movement in return mass flow. Overset mesh zero gap is used as best losing due to small gap between door and the domain. The simulation with lower angular velocity gives rise to comfortable air conditions.

KEYWORDS (one per line):

HINGED DOOR, OVERSET ZERO GAP, MASS FLOW RATE

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Project specification

The focus of the project is to analyse flow conditions or parameters that varies with time and space, unsteady (transient). The movement of the door gives rise to motion of air and this motion is fluctuating with time. As the result of this fluctuation the flow has not constant values that can be solved by mathematical methods instead computer based CFD simulation is applied to find the solution for the flow. The most well-known used software to analyse transient flow is STAR CCM+ and the same software is going to be used to analyse solution to the CFD problem.
The parameters in this case will be mass exchange, energy transport, momentum transport and pollutant transport. The movement of mass across the opening of the door in time the door opens is simulated and finally analysed its variation in the domain.
The software divides the volume domain into smaller volumes in meshing process to find solution for the problem. In our case, it is assumed to have null initial pressure whereas the movement of the door will be the main factors in driving the particles of the air in motion. Mass exchange between from one part of big domain to the other across a dividing section, door, is simulated to look its variation in the time of door moves from its initial closed state and came back to its closed state.
Energy transport (energy equations), momentum transport (momentum equations), Pollutant transport is analysed by looking its residuals in the process of simulation and this residual must converge to say that the simulation gives a good result. The desired indoor environment is predicted and controlled by controlling the factors that affect indoor environment. Air speed and mass transfer is some of the factors that affects indoor situation. Mesh analysis for moving rigid boundaries and defining the boundary conditions of the hinged door is done to get solution. The finer the mesh the better will be the result from CFD. Numerical simulations are going to be done to solve coupled of mass, momentum, and energy transport equations for this task. Overset mesh zero gap is preferred for this moving rigid boundaries because of the small gap between the door and wall of the domain. Applying filtering or filtering functions on unsteady Naiver-strokes equations to separate large eddy from small eddies and Scale resolving simulations via detached eddy simulations (DES) and its variants (modification of RANS model) is covered as a theory part in this paper. To simplify the simulation, the flow is assumed to have laminar nature. Apply finite volume method for unsteady (transient) laminar flows. Here in this method implicit unsteady is selected as a parameter for physics in our simulation.

Preface

This project is one of the projects which is proposed by oslomet to master students. The focus of this project is to simulate air flow, mass exchange and pollutant transport through a hinged door. I have interested in this type of project because it is very relevant to the present pandemic of covid 19. The focus of this project is to analyse the result of simulation done in a computer-based software, STAR CCM+.

I am a person who likes to work with computer for longer hours a day and therefor this project was not boring for me. I addition to that it is a project that simulates the movement of hinged door which is easy to understand because it is available in our everyday activities.

I would like to appreciate oslomet for alle the reference resources they made available for me. I would like to give my gratitude to Ole Melbus who guided me through the whole process. He was available at any time and that was good opportunity for me to contact him in case I need him. I would like to thank Arnab Chaudhuri, associate professor, for his help relating star ccm+ and for his quick response for mails I sent to him. I addition to that he guided me to look at related resources from OsloMet data base. I would like to thank Jørgen, who is my leader in the job I do besides, for his help regarding the work flexibility he gave in the times I need to work with my project.

I would like to give my gratitude to my wife for her patient, encouraged and support through the whole process. I would like to tank my daughter who does not complain about the time taken from her in order to make the project finished. Finally, I would like to give my pleasure to everyone who give encourage, support and moral to write this thesis successfully.

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09.06.2021

Master student

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Summary

In the first part of this paper, the theoretical background is described to show how the software is been built. Mass equation, moment equation, energy equation, transport equation and equation of state is some of the core in theoretical background. Turbulence equation and its models is also explained in detail as part of basic background toward giving good understanding of CFD methods. Applying filtering or filtering functions on unsteady Naiver-strokes equations to separate large eddy from small eddies and Scale resolving simulations via detached eddy simulations (DES) and its variants (modification of RANS model) is covered as a theory part in this paper.

The focus of this work will be the usage of overset mesh zero gap for moving rigid boundaries. This work is also very relevant to the present pandemic situation. As it mentioned above our main aim of this paperwork is to simulate hinged door and analyse the variation of the flow properties. Due to the variations of the flow properties with time and space transient flow analysis is used to get the solution. Hinged door is located between two rooms that has different initial flow properties, but it will be assumed to have the same initial properties to simplify the simulations time and effort. The door opens at a certain angular velocity and its effect up on the air around the door is visualized to analyse the data. In this case, mass flow, air velocities, transfer of energy in the form momentum and movement of pollutant is analysed from the result of the simulation. It is not easy to analyze the flow properties in transient flows because of the fluctuations of its flow properties throughout the rotation. The geometry of the domain to be simulated is created in STAR CCM+ and the created geometry is simulated in the simulation itself. The movement of the door is made to move a certain angle before it returns to its initial state of rest, and this is done by creating a suitable function that governs the motion of the door. The speed of the door can be adjusted in the function that has been created in to compare the results of simulation that simulated with different angular velocities. Screen shot of results at three different states, at the start of door opening, when the door opens fully, and when the door finally closed. In addition to that the mass flow is traced by creating a derived plane in the door opening and the results is shown in kg/s versus time. has been taken to show and compare the results to each other. This door opening as well as the movement of fluid from one room to the other will be simulated in a computer by software that use CFD method. The most known and well used software that used in this purpose is Star CCM+. To do simulation of fluid in this software, needs a strong computer that can execute handle simulations faster otherwise the simulation is going to take a lot of time.

Summary in Norwegian

I den første delen av denne artikkelen er den teoretiske bakgrunnen beskrevet godt for å vise frem hvordan programvaren er bygget på. Masseligning, momentligning, energiligning, transportligning, energiligning, transportligning og tilstandsligning er noe av de hoved delene i denne teoretiske bakgrunn. Turbulensligning sammen med dens modeller er også forklart tidlig som en del av den bakgrunnen for å gi god forståelse for CFD-metoder. Bruk av filtrerings eller filtrerinsfunksjoner på ustabile Naiver-Strokes-ligninger for å skille stor virvel fra små virvler og skalaløsningssimuleringer via frittliggende virvel-simuleringer (DES) of dens varianter (modifisering av RANS-modellen) er dekket som en teoridel i denne artikkelen.

Hoved målet for dette oppgave vil være bruken av overset mesh gap for å flytte stive grenser. Dette masteroppgaven også veldig relevant for den nåværende pandemisituasjonen. som nevnt ovenfor, er vårt hovedmål med dette oppgaven å simulere hengslet dør og analysere variasjoner i strømningsegenskapene. Transient strømningsanalyse er brukt for å få løsning fordi strømningsegenskapene variere med tid og punkt i Space. Hengslet dør er plassert mellom to rom som har forskjellige innledende flyteengskaper, men det antas å ha de samme innledende egenskapene for å forenkle simulerings eller spare tid. Døren åpnes med en viss vinkelhastighet, og effekten av den hastigheten på lufta rundt døren visualiseres for å analysere dataene. I dette tilfellet blir massestrøm, lufthastigheter, overføring av energi i form av moment og bevegelse av forurensede stoffer analysert fra resultatet av simuleringen. Det er ikke let å analysere strømningsegenskapene i forbigående strømmer på grunn av svingningen i strømningsegenskapene gjennom rotasjonen. Geometrien til Domain som skal simuleres, opprettes i samme simuleringsverktøy simuleringen skjer. Døren bevege seg en viss vinkel før den går tilbake til sin opprinnelige start punkt og dette skjer gjennom en funksjon som befinne seg i selve simuleringsverktøy. Dørens hastighet kan justeres i funksjonen og der etter simuleringsresultatene for hvert hastighetsfelt kan sammenlignes for å se effekten av de forskjellige hastigheter. Skjermbilder av resultatene i de tre forskjellige bevegelsestilstander, ved begynnelsen av døråpningen, når døren er helt åpent og når døren er i luket er tatt in resultat feltet to vise fram effekten av dør på luft rundt seg. Det er satt en 2D-Plan i døråpningen to se massestrømningen (kg/s) gjennom det planen i løpet av hele rotasjonen. Den dør rotasjonen og bevegelse på luft i domain blir simulert i en datamaskin med programvare som bruker CFD-metoden. Den meste kjente, og meste brukte programvaren som brukes i detter formålet er STAR CCM+. Dette simuleringsverktøy krever en veldig solid datamaskin for å gjøre simuleringene raskere. (translate, u.d.)

1. Introduction

The aim of the project is to analyse flow conditions or parameters that varies with time and space, unsteady (transient). The movement of the door gives rise to motion of air and this motion is fluctuating with time. As the result of this fluctuation the flow has not constant values that can be solved by mathematical methods instead computer based CFD simulation is applied to find the solution for the flow. The most well-known used software to analyse transient flow is STAR CCM+ and the same software is going to be used to analyse solution to the CFD problem.
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Energy transport (energy equations), momentum transport (momentum equations), Pollutant transport is analysed by looking its residuals in the process of simulation.
Predict / control desired indoor environment. (in this case we will predict or control the factors that play role in indoor environment like air speed, temperature, pressure, humidity, and amount of pollutant particles. Mesh analysis for moving rigid boundaries and defining the boundary conditions of the hinged door is done to get solution. The finer the mesh the better will be the result from CFD.The focus of this thesis is to do analysis on hinged doors.
Numerical simulations are going to be done to solve coupled of mass, momentum, and energy transport equations for this task. Overset mesh zero gap is preferred for this moving rigid boundaries because of the small gap between the door and wall of the domain.
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2. Background and theory

Transient flow: is the type of flow on which all the parameters is changing with respect to time change. Our focus is air flow through door opening and the movement of rigid body (door) with respect to the other bodies around it, that is the wall, the roof, and the floor. As our analysis is on air moving through the door so we are going to look at conservation of mass of compressible fluid (air). The mass balance for our fluid is written as follows.

2.1 Mass Equation in three-dimensions

Mass transfer is the process of moving mass particle from a region with high concentration to a region with low concentration, it means on the other hand this transfer is happening if and only if there is concentration difference between the regions. The term concentration is expressed as mass concentration per unit volume. On the other way we can replace concentration with a word density because they have the same meaning.
Rate of increase of mass in fluid element = net rate of flow of mass into fluid element.
The rate of increase of mass in the fluid element is.

$$\partial/\partial t(\rho\delta_x\delta_y\delta_z)=\frac{\partial\rho}{\partial_t}\delta_x\delta_y\delta_z$$

Then mass flow rate across a face of element is given by the product of density, area, and velocity component normal to the face facing. For three-dimensional body, the net rate of flow of mass into the element across its boundaries will be as follows. (Malalasekera, August 2006, ss. 10-11)

$$\dot{m} = \rho * A * u$$

$$\dot{m} = \frac{m}{L^3} * L^2 * \frac{L}{s}$$

$$\dot{m} = \frac{m}{s}$$ (Mass flow rate across a face)

$$\left(\rho_U - \frac{\partial(\rho_u)}{\partial x}\frac{1}{2}\delta_x\right)\delta_y\delta_z - \left(\rho_U + \frac{\partial(\rho_U)}{\partial x}\frac{1}{2}\delta_x\right)\delta_y\partial_z + \left(\rho_v - \frac{\partial(\rho_v)}{\partial y}\frac{1}{2}\delta_y\right)\delta_x\partial_z - \left(\rho_v\frac{\partial(\rho_v)}{\partial y}\frac{1}{2}\delta_y\right)\delta_x\partial_z +$$

Equation 2.1

The part of the equation (2.1) with the green colour is component of mass flow rate along x-axis. This can be seen clearly from the area ($\delta_y\delta_z$) on which density and velocity is multiplied with. Similarly, the blue is the mass flow rate along y-axis whereas the red is mass flow rate along the z-axis.
Flows which is directed into the element produce an increase of mass in the element and get a positive sign and those flows that are leaving the element are given negative sign. (Malalasekera, August 2006)
Equation 2.1 is rearranged and divided by element volume $\delta_x\partial_y\partial_z$ and finally gives the following formula.

$$\frac{\partial\rho}{\partial t} + \frac{\partial(\rho_U)}{\partial x} + \frac{\partial(\rho_v)}{\partial y} + \frac{\partial(\rho_w)}{\partial z} = 0 \qquad \textit{Equation 2.2}$$

Equation 2.2 can be further written in more compact form as given below.

$$\frac{\partial\rho}{\partial t} + div(\rho u) = 0 \qquad \textit{Equation 2.3}$$

Equation (2.3) is the unsteady, three-dimensional mass conservation or continuity equation at a point in a compressible fluid. (Malalasekera, August 2006, ss. 10-11)

2.2 Momentum equation in three-dimensional

Newton’s second law states that the rate of change of momentum of a fluid particle equals the sum of forces on the particle.

The forces which is acting on a particle are categorized as surface forces and body forces. The surface forces are pressure forces, viscous forces, and gravity force whereas the body forces are centrifugal force, Coriolis force and electromagnetic force. (Malalasekera, August 2006, s. 15)

Let us demonstrate our body and the forces which is acting on it.

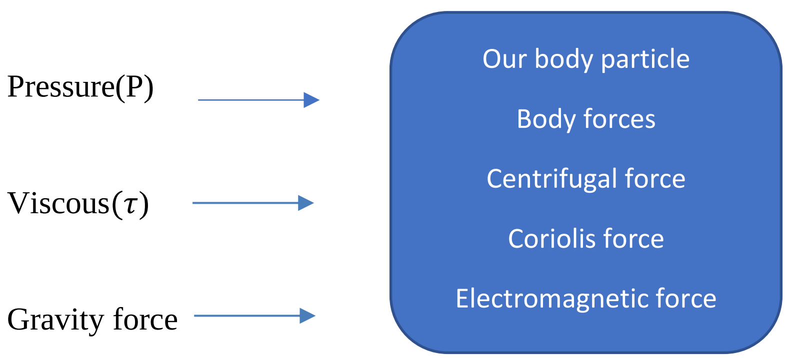

Figure 1 Forces acting on a particle.

As it mentioned above, rate of change of momentum equals the sum of the forces on it. This can be written with an equation as follows.

Momentum is the product of mass and velocity men rate of change in momentum is the product of mass and velocity divided by the change in time.

$$\dot{M} = \frac{m\Delta u}{\Delta t}$$

$$\dot{M} = \frac{mDu}{Dt}$$ Equation 2.4

Whereas m=$\rho * v$ Equation 2.5

Putting equation (2.5) into equation (2.4) we get another equation.

$$\dot{M} = \frac{\rho * v * Du}{Dt}$$ Equation 2.6

Dividing equation (2.6) by a unit volume of fluid particle we get another simplified formula.

$\dot{M} = \frac{\rho * v * Du}{v * Dt}$

$\dot{M} = \frac{\rho * Du}{Dt}$ along x-axis $\dot{M} = \frac{\rho * Dv}{Dt}$ along y-axis $\dot{M} = \frac{\rho * Dw}{Dt}$ along z-axis

It is common practice to highlight the contributions due to the surface forces as separate terms in momentum equation and to include the effect of body forces as source terms. (Malalasekera, August 2006, s. 14)

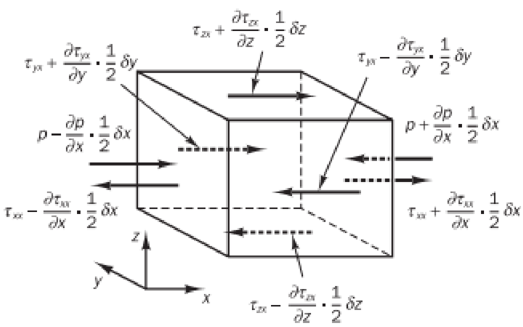

Figure 2 stress component on the x-axis

Let us start from compute forces on the east and west side as one pair. The sign of the vector force facing the right is positive whereas the others which is facing the left has a negative sign.

$[(p - \frac{\partial P}{\partial x}\frac{1}{2}\delta x)\text{-}(\tau_{xx} - \frac{\partial \tau_{xx}}{\partial x}\frac{1}{2}\delta_x)]\delta_y\delta_z + [\text{-}((p + \frac{\partial P}{\partial x}\frac{1}{2}\delta x)\text{+}(\tau_{xx} + \frac{\partial \tau_{xx}}{\partial x}\frac{1}{2}\delta_x)]\ \delta_y\delta_z =$
$(-\frac{\partial P}{\partial x}\text{+}\frac{\partial \tau_{xx}}{\partial x})\ \delta_x\delta_y\delta_z$ Equation 2.7

Next comes the net force facing north and south.

$(\tau_{yx} - \frac{\partial \tau_{yx}}{\partial y}\frac{1}{2}\delta_y)\delta_x\delta_z \text{+}(\tau_{yx} + \frac{\partial \tau_{yx}}{\partial y}\frac{1}{2}\delta_y)\delta_x\delta_z\text{=}\ \frac{\partial \tau_{yx}}{\partial y}\ \delta_x\delta_y\delta_z$ Equation 2.8

At the end will be the face on the top and bottom.

$$-(\tau_{zx} - \frac{\partial \tau_{zx}}{\partial z}\frac{1}{2}\delta_z)\delta_x\delta_y + (\tau_{zx} + \frac{\partial \tau_{zx}}{\partial z}\frac{1}{2}\delta_z)\delta_x\delta_y = \frac{\partial \tau_{zx}}{\partial z}\ \delta_x\delta_y\delta_z \qquad \text{Equation 2.9}$$

From those three formulas we can deduce the total force per unit volume due to surface stresses is equal the sum of (2.7), (2.8) and (2.9) divided by the unit volume $\delta_x\delta_y\delta_z$

$$-\frac{\partial P}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} \qquad \text{Equation 2.10}$$

Momentum equation along x-axis is equal sum of to total surface stresses and source along that axis. This can be shown as follows in the equation below.

$$\rho\frac{Du}{Dt} = \frac{\partial(-p+\tau_{xx})}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} + S_{M_x} \qquad \text{Equation 2.11}$$

The rate of momentum in this case has two forces along the x-axis that is stress force and pressure force that is why it has been done derivative on both this forces with respect ∂x whereas in the other two axis, y and z axis, is only stress force available on the surface. The same way can be written components of momentum along y and z-axis.

Momentum equation along y-axis**.** The y-component of momentum equation is given as follows.

$$\rho\frac{Dv}{Dt} = \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial(-p+\tau_{yy})}{\partial y} + \frac{\partial \tau_{zy}}{\partial z} + S_{M_y} \qquad \text{Equation 2.12}$$

The rate of momentum in this case has two forces along the y-axis that is stress force and pressure force that is why it has been done derivative on both this forces with respect ∂y

Momentum equation along z-axis. The z-component of momentum equation is given as follows.

$$\rho\frac{Dw}{Dt} = \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial(-p+\tau_{zz})}{\partial z} + S_{M_z} \qquad \text{Equation 2.13}$$

The rate of momentum in this case has two forces along the y-axis that is stress force and pressure force that is why it has been done derivative on both this forces with respect ∂z

The source terms ($S_{M_x}, S_{M_x}, S_{M_x}$) in the three equations (2.11), (2.12) and (2.13) represent the contribution due to body forces. This body forces must be added to the surface forces to give more accurate results of momentum along the different axis. To have a good picture of this let us mention one example. The body force due to gravity would be modelled by assigning the source field on x and y axis to zero whereas the other body source S_{M_z}= -ρg (Malalasekera, August 2006, s. 16)

2.3 Energy equation in three dimensions

first law of thermodynamics states that the rate of change of energy of a fluid particle is equal to the rate of heat addition to the fluid plus the rate of work don on the particle. Based on the above-mentioned law that energy equation is formulated and derived.

As we know the relation between energy and momentum can be expressed as follows

E= $\frac{1}{2}mv2$

Whereas momentum is mv

Multiplying momentum with the velocity vector we can get energy.

Let us see the rate of work done by surface forces on each axis.

$$[\,(pu-\frac{\partial(Pu)}{\partial x}\frac{1}{2}\delta x\,)\text{-}(\tau_{xx}u-\frac{\partial(\tau_{xx}\,u)1}{\partial x\quad 2}\delta_x)]\delta_y\delta_z + [\text{-}(pu+\frac{\partial Pu}{\partial x}\frac{1}{2}\delta x)\text{+}(\,\tau_{xx}u+\frac{\partial(\tau_{xx}u)}{\partial x}\frac{1}{2}\delta_x)]\,\delta_y\delta_z + (\tau_{yx}u-\frac{\partial(\tau_{yx}u)}{\partial y}\frac{1}{2}\delta_y)\delta_x\delta_z + (\tau_{yx}u+\frac{\partial(\tau_{yx}\,u)1}{\partial y\quad 2}\delta_y)\delta_x\delta_z + -(\tau_{zx}u-\frac{(\partial\tau_{zx}u)}{\partial z}\frac{1}{2}\delta_z)\delta_x\delta_y + (\tau_{zx}+\frac{\partial\tau_{zx}}{\partial z}\frac{1}{2}\delta_z)\delta_x\delta_y \qquad \text{Equation 2.14}$$

x-component of the work done.

$$[\frac{\partial(u(-p+\tau_{xx})}{\partial x}+\frac{\partial(u\tau_{yx})}{\partial y}+\frac{\partial(u\tau_{zx})}{\partial z}]\,\delta_x\delta_y\delta_z \qquad \text{Equation 2.15}$$

y-component of the work done.

$$[\frac{\partial(v\tau_{xy}\,)}{\partial x}+\frac{\partial(v(-p+\tau_{yy})}{\partial y}+\frac{\partial(v\tau_{zy})}{\partial z}]\,\delta_x\delta_y\delta_z \qquad \text{Equation 2.16}$$

z-component of the work done.

$$[\frac{\partial(w\tau_{xz)}}{\partial x} + \frac{\partial(w\tau_{yz)}}{\partial y} + \frac{\partial(w(-p+\tau_{zz)})}{\partial z}]\ \delta_x\delta_y\delta_z \qquad \text{Equation 2.17}$$

The total rate of work done per unit volume will be simplified to the following formula. Alle the terms that has pressure can be computed to its simplest vector form in the formula given below. One of the simplifying functions we have used is divergence function. (2.18) (Malalasekera, August 2006, s. 17)

$$-\nabla(pu) = -\frac{\partial(up)}{\partial x}\frac{-\partial(vp)}{\partial y}\frac{-\partial(wp)}{\partial z}$$

$-\nabla(pu)$ = -div(pu)

The total rate of work done per unit volume.

$$[\text{-div}(pu)] + [\ \frac{\partial(u\tau_{xx})}{\partial x} + \frac{\partial(u\tau_{yx})}{\partial y} + \frac{\partial(u\tau_{zx})}{\partial z} + \frac{\partial(v\tau_{xy})}{\partial x} + \frac{\partial(v\tau_{yy})}{\partial y} + \frac{\partial(v\tau_{zy})}{\partial z} + \frac{\partial(w\tau_{xz})}{\partial x} + \frac{\partial(w\tau_{yz})}{\partial y} + \frac{\partial(w\tau_{zz})}{\partial z}$$

Equation 2.18

Equation (2.18) has to component of forces one is the force due to pressure og the other is surface stresses and this show god overview of the forces acting on our required fluid particle. To make the equation more simplified it has been written per unit volume so that the term $\delta_x\delta_y\delta_z$ removed.

Energy flux due to heat energy

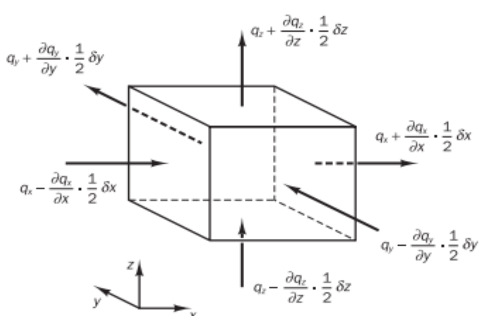

Figure 3 flux components acting on the body.

Dealing with heat energy is not only scaler terms are available but also direction which makes it a little bit complex. The vector force in this case is the heat flux q and this q has three components one on each axis. The three heat flux components are q_x, q_y, q_z.

The net rate of heat transfer to the fluid particle along x-axis

$$\left[\left(q_x - \frac{\partial q_x}{\partial x}\frac{1}{2}\delta x\right) - (q_x + \frac{\partial q_x}{\partial x}\frac{1}{2}\delta x)\ \right] \delta_y \delta_z = - \frac{\partial q_x}{\partial x}\, \delta_x \delta_y \delta_z$$

The net rate of heat transfer to the fluid particle along y-axis

$$- \quad \frac{\partial q_y}{\partial}\, \delta_x \delta_y \delta_z$$

The net rate of heat transfer to the fluid particle along z-axis

$$- \quad \frac{\partial q_z}{\partial z}\, \delta_x \delta_y \delta_z$$

The total rate of heat added to the fluid particle per unit volume due to heat flow across its boundaries is given as follow below (Malalasekera, August 2006, s. 18)

$$- \quad \frac{\partial q_x}{\partial x} - \frac{\partial q_y}{\partial} - \frac{\partial q_z}{\partial z} = \text{-divq} \qquad \text{Equation 2.19}$$

After it has been through the basic equations of work done and heat flux on our target fluid particle came to final energy equation. The whole energy equation is written down her.

$$\rho \frac{DE}{Dt} = \text{-div(pu)} + \left[\ \frac{\partial(u\tau_{xx})}{\partial x} + \frac{\partial(u\tau_{yx})}{\partial y} + \frac{\partial(u\tau_{zx})}{\partial z} + \frac{\partial(v\tau_{xy})}{\partial x} + \frac{\partial(v\tau_{yy})}{\partial y} + \frac{\partial(v\tau_{zy})}{\partial z} + \frac{\partial(w\tau_{xz})}{\partial x} + \frac{\partial(w\tau_{yz})}{\partial y} + \frac{\partial(w\tau_{zz})}{\partial z}\ \right] +$$

$$\text{div (k grad T)} + S_E \qquad \text{Equation 2.20}$$

2.4 Equation of state

To deal with the equation of a state, we need to know the variable that describe the state of a material.

The variable that describes the state of a material (Gas, liquid or solid) are called the state variable. Density (ρ), pressure (p), internal energy (i) and Temperature (T) are some of the state variables. Equation of state relates one state variable to the other to state variables. For example, let us see how it is related in the following equation. (Malalasekera, August 2006, s. 20)

$$p = p\,(\rho, T) \quad and \quad i = (\rho, T) \qquad \textit{Equation 2.21}$$

in the flow of compressible fluids, the equations of state provide the linkage between the energy equation on the one hand and mass conservation and momentum equation on the other.

2.5 Transport equations

Transport equation is used to describe all fluid flow equations, including scalar quantities such temperature and pollutant concentration etc. In this general equation we can denote the quantity with the variable ϕ and this show as follows in the equation (2.22)

$$\frac{\partial(\rho\phi)}{\partial t} + div(\rho\phi U) = div[\Gamma\ grad\ \phi] + S_\phi \qquad \textit{Equation 2.22}$$

The first term on the left side of transport equation is the rate of change term where is the second term is the convective term.
Diffusive term and source term located one after the other on the right side of the transport equation.
If we integrate equation (2.22) over the three-dimensional control volume (CV):

$$\int_{Cv} \frac{\partial(\rho\phi)}{\partial t}\, dV + \int_{cv} div(\rho\phi U)\, dV = \int_{cv} div[\Gamma\ grad\ \phi]\, dV + \int_{cv} S_\phi dV \qquad \textit{Equation 2.23}$$

Applying Gauss's divergence theorem, equation (2.23) can be written as follows.

$$\frac{\partial}{\partial t}\left[\int_{cV} \rho\phi\, dV\right] + \int_A n.(\rho\phi U)\, dA = \int_A n.[\Gamma\ grad\ \phi]\, dA + \int_{cv} S_\phi dV \qquad \textit{Equation 2.24}$$

After we are applying the Gauss's theorem, the first term in equation (2.24) signifies the rate of change of the total amount of fluid property ϕ in the control volume whereas the second term on the left side is the convective term. This term expresses the net rate of decrease of fluid property ϕ of the fluid element due to convection.

The first term on right hand side of equation (2.24) is the diffusive term and expresses the net rate of increase of fluid property ϕ of the fluid element due to diffusion. The final term on the right-hand side gives the rate of increase of property ϕ as a result of source. (Malalasekera, August 2006, ss. 24-26)
In time- dependent (transient) problems, equation (2.24) will be integrated from t to t+Δt and gives us the following formula.

$$\int_{\Delta t} \frac{\partial}{\partial t}\left[\int_{cV} \rho\phi \, dV\right] + \int_{\Delta t}\int_{A} n.(\rho\phi U)\, dA = \int_{\Delta t}\int_{A} n.[\Gamma \, grad\, \phi]\, dA + \int_{\Delta t}\int_{cv} S_{\phi} dV \quad \textit{Equation 2.25}$$

2.6 Turbulent flow calculation methods

Turbulence flow is the type of flow where the fluctuations happen in a very complex way, and it is more significant in less viscous fluids. In other, turbulence flow is three-dimensional chaotic fluctuation of a fluid. Less viscous fluids with high velocity turns out to be more turbulent and on the other side more viscous fluids with less velocity are laminar in nature.

2.6.1 Turbulence models for Reynolds-averaged Navier-stokes (RANS) equations.

This type of turbulence equation method is computed on the time-averaged of the control properties. Time averaging of the control properties does not gives full information about the flow. Turbulence models is very important when you want to solve the momentum, energy of continuity equation using RANS equations. This model helps to predict the Reynolds stresses and scalar transport terms. STAR-CCM+ uses two approaches to handle mean flow quantities and provide closure of the governing equations, Eddy viscosity model and Reynolds stress transport models. (Siemens)

To mention some of the turbulent models are mixing length model (zero degree), k-ε model and k-w (degree two), Reynolds stress model. The most common of this is the k-ε model and k-w. “These models form the basis of standard turbulence calculation procedures in the currently available CFD codes. (Malalasekera, August 2006, s. 67)

2.6.1.1 Mixing length model

Prandtl mixing length modeling is type of modeling that uses length scale and its formula written as follows:

$v_t = Cvl$

$v_t(\frac{m2}{s})$ is the kinematic turbulent viscosity.

$v\left(\frac{m}{s}\right)$ is the velocity.

$l(m)$ is the length.

C dimensionless constant

$v = \text{cl}\left|\frac{\partial u}{\partial y}\right|$

$$v_t = l_m^2 \left|\frac{\partial U}{\partial y}\right| \quad \textit{Equation 2.26}$$

Reynolds stress can be expressed like this.

$$\tau_{xy} = \tau_{yx} = -\rho\overline{u'v'} = \rho l_m^2 \left|\frac{\partial U}{\partial y}\right| \frac{\partial U}{\partial y} \quad \textit{Equation 2.27}$$

Siden most of the kinetic energy of turbulent flow is contained in largest eddies so length scale of the large eddies is used as mixing length modeling. This type of modeling works good in 2D turbulent flows. (Malalasekera, August 2006, s. 70)

This type of modeling is very cheap and simple to implement but it is incapable of modeling flows with separation and recirculation because it only calculates the mean value properties and turbulent shear stress.

2.6.1.2 The k-ε model

The K-Epsilon turbulence model is a two-equation model that solves transport equations for the turbulent kinetic energy K and the turbulent dissipation rate ε to determine the turbulent eddy viscosity (Siemens)

This type of modeling is applied to flows where convection and diffusion causes are significant and this modeling focuses on mechanisms that affect the turbulence kinetic energy. (Malalasekera, August 2006, s. 72)

In this type of modeling, we have two model equations, one for k and one for ε so velocity and length scale can be represented by k and ε as follows below. Dissipation of turbulent kinetic energy dominates in the smalles eddies this happens because the large eddies extract energy from the flow and transfer this energy to the smaller ones and the smaller ones to the very smaller and so on until it reaches to the smallest eddies.

$u = k^{\frac{1}{2}}$ where as $l = \frac{k^{3/2}}{\varepsilon}$

So eddy viscosity can be written as follows

$\mu_t = C\rho v l = \rho C\mu \frac{k^2}{\varepsilon}$ where $C\mu$ is a dimension less constant.

In this type of model uses transport equation for k and ε as in the equations (2.28) and (2.29)

$$\frac{\partial(\rho k)}{\partial t} + div(\rho k U) = div\ [\frac{\mu_t}{\sigma_k} grad\ k\ ] + 2\ \mu_t s_{ij*} s_{ij} - \rho\varepsilon \qquad \textit{Equation 2.28}$$

$$\frac{\partial(\rho\varepsilon)}{\partial t} + div(\rho\varepsilon U) = div\ [\frac{\mu_t}{\sigma_\varepsilon} grad\ \varepsilon\ ] + c_{1\varepsilon}\frac{\varepsilon}{k} 2\ \mu_t s_{ij*} s_{ij} - c_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \qquad \textit{Equation 2.29}$$

The first term on the left side is the rate of change of k or ε and the second term on left side is the transport of k or ε by convection. On the other hand, the first term on the right side is the transport of k or ε by diffusion whereas the second term is the rate of production of k or ε og last term of the equations is the rate of destruction of k or ε. (Malalasekera, August 2006, s. 75)
The distribution of k and ε around the boundaries must be either assumed or evaluated as follows.
In the inlet the distribution must be given whereas in the outlet, symmetry axis and on free stream the partial derivative is zero for both ($\frac{\partial k}{\partial_n}$ =0, $\frac{\partial \varepsilon}{\partial_n} = 0$). Boundary condtion on solid walls depends on Reynolds number, for high Reynolds number uses wall function approach whereas the low Reynolds number uses damping function approach.
This type of modeling is most widely validated turbulence model with excellent performance for many industrial applications even though it has some drawbacks. To mention some of its

drawbacks is more expensive than mixing length model and it is not suitable for unconfined flows, rotating flows, and fully developed flows in circular ducts.

2.6.1.3 Reynolds stress equation models

Reynolds stress equations model (RSM) is the most complex turbulence model. It is also known as second-moment closure model.

This type of modeling has the following positive thing and drawbacks.

Her it is only the initial and boundary conditions which is needed to model the flow and it is relatively accurate for calculating the average value of the flow properties and all Reynolds stresses.

On the other hand, it has the following drawbacks.

It is expensive to use this method to compute the flow properties, it is not well known and validated as the two above mentioned modeling and it is not good in performance.

2.6.1.4 Advanced turbulence models

Advanced turbulence model is developed to overcome the drawbacks of k-ε. Let us mention som of shortcomings of k-ε which is addressed by advanced turbulence models.

Low Reynolds number flows, rapidly changing flows, stress anisotropy, strong adverse pressure gradient and recirculation region and extra strains are some the drawbacks which is addressed by advanced turbulence model. (Malalasekera, August 2006, s. 86)

2.6.2 Large eddy simulation

In this type of simulation, the large eddies have been tracked and filtered from the rest of small eddies using what is known as sub grid-scale model. It means on the other way that it uses filter to allow to pass the large eddies and reject the small ones. This type of technique is mostly used on transient flow rather than steady flow. In simcenter Star-CCM+, implicit filtering is used. For this approach, the computational grid determines the scale of the eddies that are filtered out. Implicit filtering takes full advantage of the grid resolution and is, in general, computationally less expensive than explicit filtering. (Siemens)

2.6.2.1 Spatial filtering of unsteady Navier-Stokes equations.

Filters are the most used separation devices in electronic devices, and it is made to split one signal or other form from another which has different properties than the target property. By doing this it creates to parts, the needed ones which we call retained part and the undesirable which is the rejected part. Filters use filtering functions with the required cutoff width. As the name implies her, filtering is performed in three-dimensional space. Our velocity vector has three components, one on each axis (x, y, z). The unsteady Navier-strokes equation for fluid with constant viscosity μ is as follows.

$$\frac{\partial_\rho}{\partial t} + div(\rho u) = 0 \qquad \textit{Equation 2.30}$$

$$\frac{\partial(\rho U)}{\partial t} + div(\rho uu) = -\frac{\partial P}{\partial x} + \mu\, div(\, gra\, d(u)) + S_u$$

Equation 2.31

$$\frac{\partial(\rho v)}{\partial t} + div(\rho vu) = -\frac{\partial P}{\partial y} + \mu\, div(\, gra\, d(v)) + S_y$$

Equation 2.32

$$\frac{\partial(\rho w)}{\partial t} + div(\rho wu) = -\frac{\partial P}{\partial z} + \mu\, div(\, gra\, d(w)) + S_w$$

Equation 2.33

This equation can be simplified for incompressible fluids, as we have div(u) = 0 and as the result the viscous momentum source terms S_u, S_y, S_w are zero.
Applying filtering function on the above equation, we get filtered equations and the variables in the filtered equations are denoted by overbar.

$$\frac{\partial(\rho \overline{U})}{\partial t} + div(\rho \overline{U}\overline{U}) = -\frac{\partial \overline{P}}{\partial x} + \mu\, div(grad(\overline{U})$$

Equation 2.34

$$\frac{\partial(\rho \overline{v})}{\partial t} + div(\rho \overline{v}\overline{U}) = -\frac{\partial \overline{P}}{\partial y} + \mu\, div(grad(\overline{v})$$

Equation 2.35

$$\frac{\partial(\rho \overline{w})}{\partial t} + div(\rho \overline{w}\overline{U}) = -\frac{\partial \overline{P}}{\partial z} + \mu\, div(grad(\overline{w})$$

Equation 2.36

2.6.2.2 Smagorinsksy-lilly SGS model

In this type of modeling good predictions of Reynolds-averaged turbulent stresses by taking into consideration that

(1) The change in the flow direction must be slow to give balanced production and dissipation of turbulence.

(2) The structure of turbulence must be isotropic, or the gradients of the anisotropic normal stresses should not be dynamically active.

This model is based on Boussinesq assumption of constant SGS eddy viscosity to connect SGS stresses and resolved-flow stain rates. (Malalasekera, August 2006, s. 104)

2.6.3 Direct numerical simulation (DNS)

It is the type of simulation technique that computes not the large eddies but the mean flow and rest of turbulent fluctuations.

Direct numerical simulation (DNS) of turbulent flow uses continuity and Navier- Stokes equation as a starting point and evaluate solution by meshing the required space with small time steps. This is method is also trying to handle smallest eddies and fastest fluctuation to came up with more accurate results.
In this type of simulation, the Navier-Stokes equations are numerically solved without the need for turbulence modeling. All the spatial scale of the turbulence must be resolved in computational mesh, starting the smallest dissipative scales (Kolmogorov microscales), up to the integral scale L. (Wikipedia, 2020)

2.7 The finite volume method for diffusion problems

Let us see the governing equation of steady diffusion by deleting the transient and convective terms of the general transport equation for property $\emptyset$

$$div(\Gamma\, grad\, \emptyset) + S_{\emptyset} = 0$$

Equation 2.37

integrating the above equation on the control forms finite volume method and integration of the diffusion equation is shown as follows (Malalasekera, August 2006, s. 115)

$$\int_{cv} div(\Gamma\, grad\, \emptyset)\, dV + \int_{Cv} S_{\emptyset} dV = \int_{A} n.(\Gamma\, grad\, \emptyset) dA + \int_{Cv} S_{\emptyset} dV = 0$$

Equation 2.38

2.7.1 Finite volume method for one dimensional steady state diffusion

We will assume our steady state diffusion of the property by ϕ so diffusion equation can be written as follows.

$$\frac{d}{d_x}\left(\Gamma \frac{d\emptyset}{dx}\right) + s = 0$$

Γ is the diffusion coefficient.

s is the source.

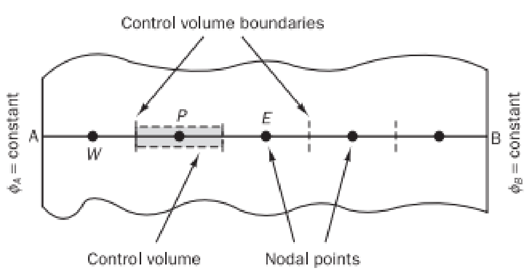

Figure 4 shows control volume with its boundaries picked from (Malalasekera, August 2006, s. 116)

Finite volume method can be solved by following important steps.

The first step to be used is to divide the region into smaller control volumes. To make easier to understand the concept of dividing into smaller volumes, it will be showed in one dimensional. Let us draw a line a divide the line into several nodes. After that it will be done integration of the governing equation over a control volume. In one dimension it uses central differencing that is linear approximate distribution of properties between nodal points is used.

Finally, discretized equation of each nodal points is formed to solve problem. finite volume method is showing on one dimension to understand the concept of solving the problem but in real life problem it is three dimensional, that will be a little more complex to solve them.

2.8 Solution of discretized equations

It is not easy to get solution of the governing equation by solving them directly but instead the differential equations will be replaced with suitable algebraic equation. There so many ways of transforming differential equations to linear algebraic equation. Differential equations can be changed into linear algebraic equation by direct and indirect or iterative methods. The direct method is done by using Cramer's rule matrix inversion or Gaussian elimination method whereas the iterative methods are based on the repeated application of a relatively simple algorithm leading to convergence. Jacobi and Gauss-Seidel point -iterative method is one example of iterative method. (Malalasekera, August 2006, s. 212)

3. Methods and Materials

As it mentioned above our main aim of this paperwork is to simulate hinged door and analyse the variation of the flow properties. Due to the variations of the flow properties with time and space transient flow analysis is used to get the solution. Hinged door is located between two rooms that has different initial flow properties, but it will be assumed to have the same initial properties to simplify the simulations time and effort. The door opens at a certain angular velocity and its effect up on the air around the door is visualized to analyse the data. In this case, mass flow, air velocities, transfer of energy in the form momentum and movement of pollutant is analysed from the result of the simulation. It is not easy to analyse the flow properties in transient flows because of the fluctuations of its flow properties throughout the rotation. The geometry of the domain to be simulated is created in STAR CCM+ and the created geometry is simulated in the it. The movement of the door is made to move a certain angle before it returns to its initial state of rest, and this is done by creating a suitable function that governs the motion of the door. The speed of the door can be adjusted in the function that has been created in to compare the results of simulation that simulated with different angular velocities. Screen shot of results at three different states, at the start of door opening, when the door opens fully, and when the door finally closed. In addition to that the mass flow is traced by creating a derived plane in the door opening and the results is shown in kg/s versus time. has been taken to show and compare the results to each other. This door opening as well as the movement of fluid from one room to the other will be simulated in a computer by software that use CFD method. The most known and well used software that used in this purpose is Star CCM+. To do simulation of fluid in this software, needs a strong computer that can execute handle simulations faster otherwise the simulation is going to take a lot of time.

Let us see how the software works.

First, the figure on which it includes the fluid has be drawn in the software or it can be imported to the software but in my case, I have drawn it in the software. After I have drawn my figure, so I defined the boundary condition, and I gave the name of each face in the boundary condition to distinguish from each other. This face are the parts of the figure which to be assigned to a region. In my case I have more than one region which interacts on each other. Meshing is done to the created regions and meshing helps the software to divide into small volume. The program software will integrate the small regions to get the result for the whole region. The finer the meshing the better the results will be achieved from the simulation this is because the system covers up to the smallest part of the region. the main drawback of having finer meshing is the time it takes to execute the volume cells. In this software you can also define stopping criteria for the simulation to stop to the predefined stopping criteria. Initial conditions of the flow properties are assigned to a suitable value.

In my case we have hinged door that moves with respect the wall, roof, and floor so we will be using overset mesh zero gap on the regions between the moving part and the part which do not move. Let us see the steps I used to simulate the movement of hinged door and analyze the results. The first step is geometry creation, this can either be created in the simulating software Star CCM+ or it can be created in other compatible software and import the finished geometry in our simulating program. In my case her , the geometry is been created in the software itself instead of importing from other CAD software.

3.1 Geometry creation

After opening the simulating software, click on file and then select new to create a new geometry. I have used parallel on local host as a process option and power on demand with a proper key to open the simulation. click geometry > 3D-CAD models and select new geometry. Choose the appropriate plane that suits your drawing, for simplicity I have chosen the XY plane to draw my geometry. Firstly, the hinged door is drawn, extruded a certain height and then on top of the hinged door comes my overset mesh. The overset mesh is drawn to cover the whole hinged door around all sides with equal overset thickness. To separate the hinged door from the overset mesh Boolean operation must be done. In this case I have used the most used Boolean operation, subtract, to subtract the hinged door from overset mesh. In creating the bodies, I have used imprint as a body interaction. The final figure left is the domain that includes all the bodies in it. The domain has been drawn around the overset and hinged door with no interaction with them. The floor, roof and walls have a very small gap (2mm) with the hinged door. As a result of this narrow gap between the door and faces of the domain, zero gap overset mesh method is preferred as a good option for instead of using overset mesh. The overset mesh which is outside of the domain does not play any role in the interaction between the overset and the domain. Finally, the 3D-CAD is closed to go further to the next step of the process, creating new geometry parts.

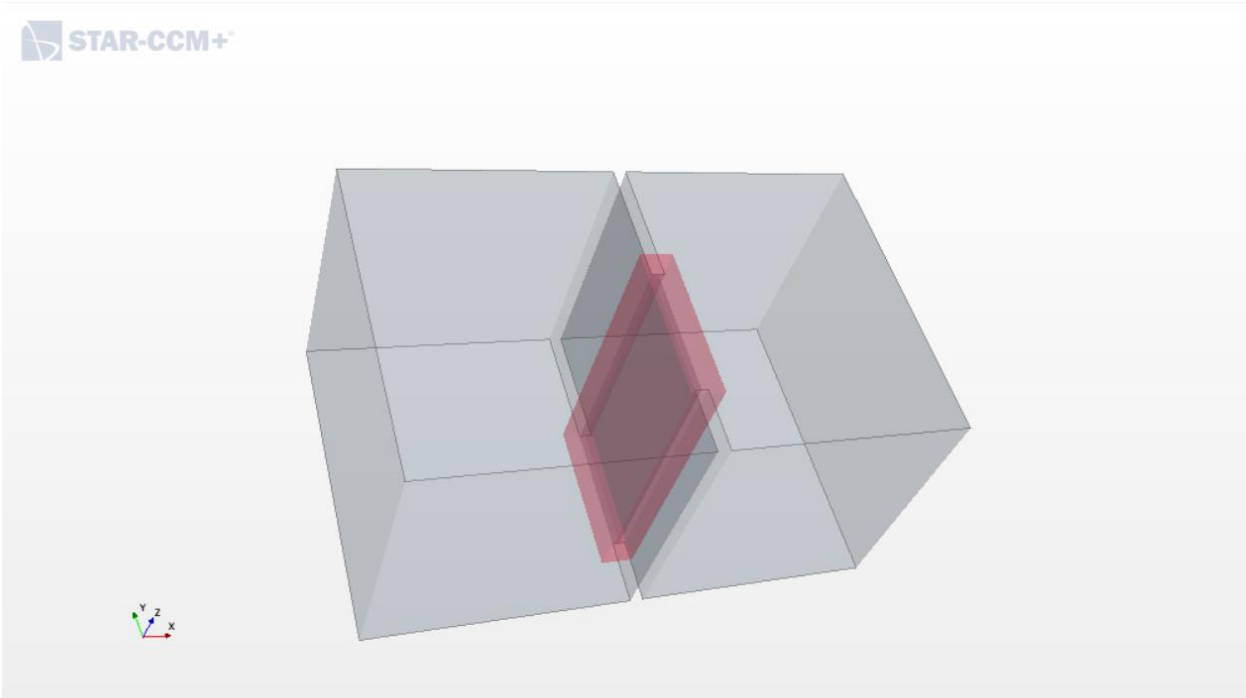

Figure 5 geometry created STAR CCM+

3.2 Define parts, regions.

It has been assumed the whole volume is closed from external environment and the only movement of air will be the movement from one room to the other room when the door opens. After 3D-CAD model is created then closed so go to geometry > 3D-CAD model > 3D-CAD HINGED DOOR MODEL > right click and select new geometry parts and then part will be created. The part that has been created has only one name for alle the faces, but the faces of the parts will be given names by right clicking on the default face name and then click split by patch to form different name for the faces. The big domain will be having the roof, floor, and the wall surfaces around. Our overset mesh body surface will be having four boundaries one the inside faces which does not have contact with air in the domain, the second will be the external surfaces which has an overset contact with the air in the room, the third is the face facing the roof, and the fourth is the face facing the floor. It is not necessary to create part for the door because the inside boundary inside the overset mesh represents the door. After boundary names has been assigned so regions are going to be created. Two regions is created, one for the overset mesh region and the other for the domain region. To create a region, click on the part on which the region to be created and then go to assign part to region and choose from the window panel these options create a region for each part, create a boundary for each part surface, create a feature curve for each part curve and do not create an interface from contacts then finally apply to create a region. The same procedure will used to create region for the remaining part. Open the regions that has been created and check if the boundaries has been created properly after that open the outer boundary of the overset mesh and change the type from wall to overset and leave the other boundaries as “walls”.

After physics has been created and meshing is made, the motion specification of the overset mesh can be changed from stationary to rotating but rotation must be created before that. Let us see how to create rotation in STAR CCM+.

Go to tools > motion > new > rotation. The z-component of the axis direction is set to 1 because our chosen axis direction in this is on the z-axis and leave the axis origin as it is because the tip of the moving door is drawn on the null point. The difficult part in making rotation is to define rotation rate in such a way that the door can go a certain angle and come back to its initial state. To make rotation rate, some function must be used that describe our motion. Let us see some of the function taken from STAR CCM+ guidebook that used to describe the rotation of the hinged door.

`($Time<=X) ? Y : (($Time>X && $Time<2X) ? -Y : 0.0)` Equation 3.1

X represents time taken in seconds.

Y represents angular velocity in rad/s.

The equation 5.1 above has “Y” angular velocity per second for every time less or equal to X and has “-Y” for every time between X and 2X and for other every time, not included in the above two situations, the angular velocity will be zero.

From mathematic concept of view one full rotation (360 degrees) is equal to $2 * \pi *$rad = 6.28 radians

it is assumed that the door opens to an angle around 90 degrees, and this will be 1.57 in radians. At the end, the opening of the door is approximated to 1.5 rad.

If the door opens with one second time and closes with almost one second time so the function will be written as follows

`($Time<=1) ? 1.5 : (($Time>1 && $Time<0.2) ? -1.5 : 0.0)` Equation 3.2

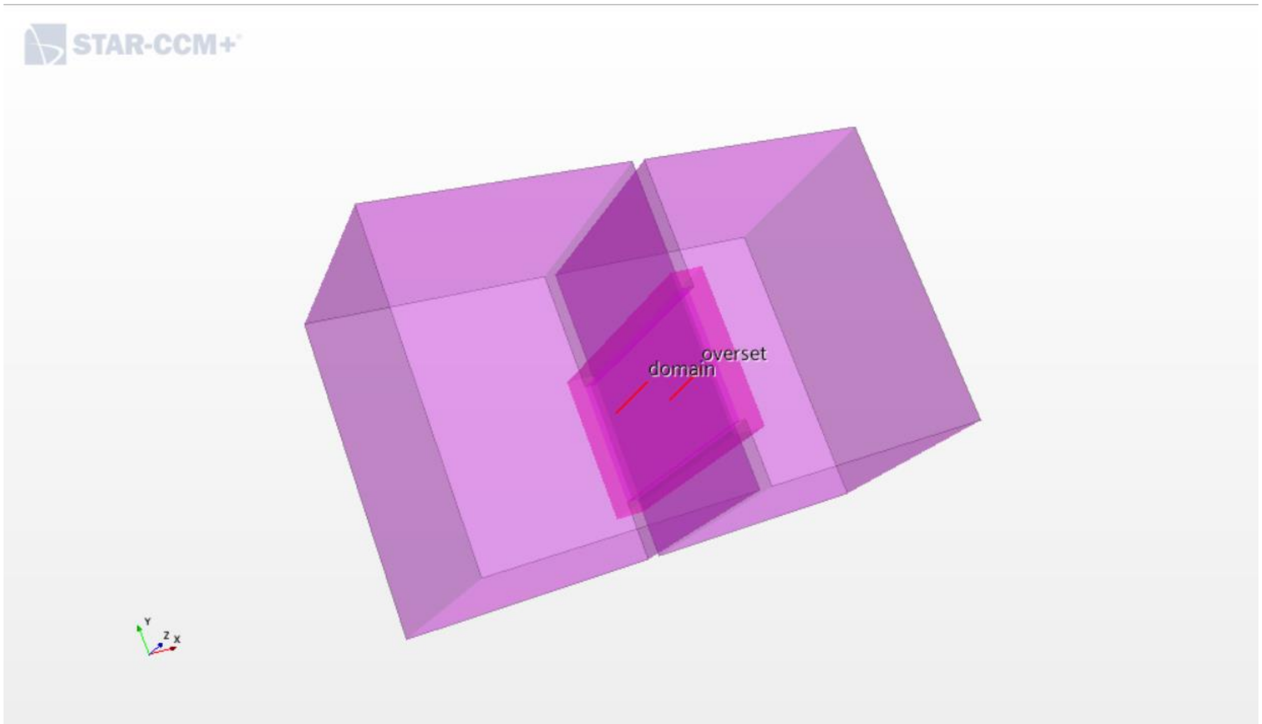

Figure 6 Overset mesh boundaries.

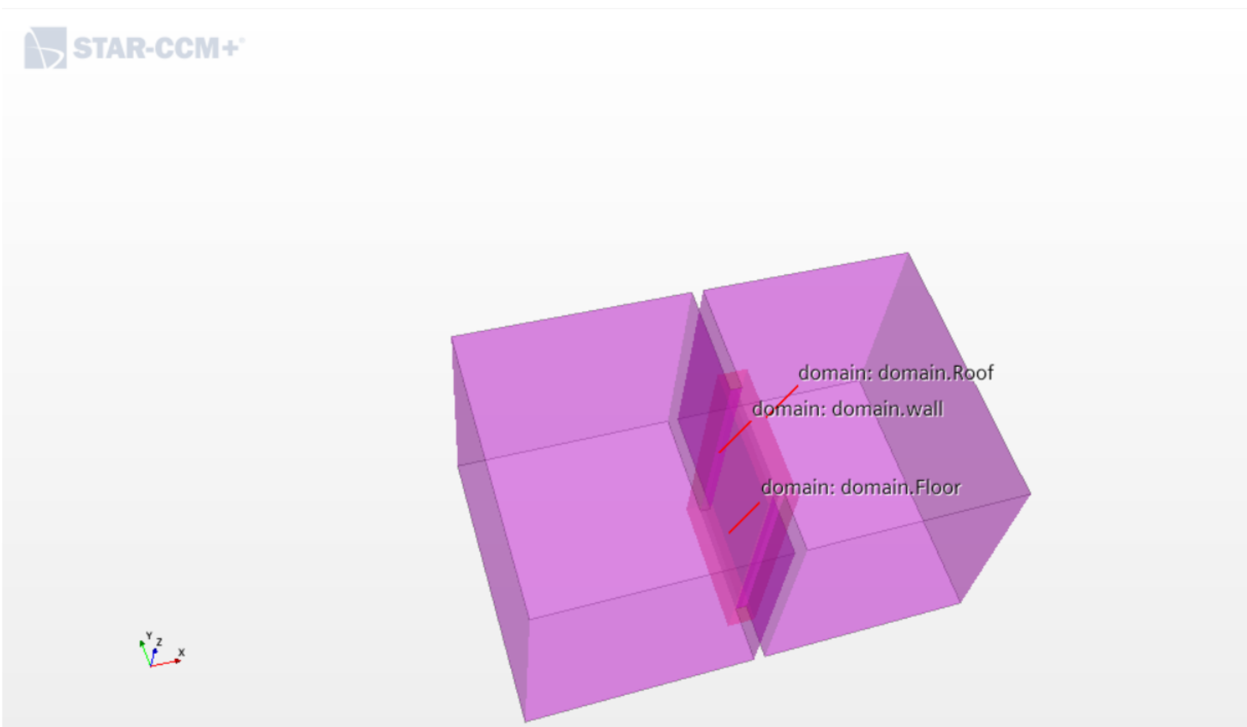

Figure 7 Domain boundaries

3.3 mesh creation

In this specific case we are going to implement automated mesh for the two regions, and it will be applied surface remesher, trimmed cell mesher and prism layer mesher. The base size and some properties will be adjusted to get finer mesh whereas the default value of the other properties will be accepted as it is to simplify the simulation. The three meshing methods used in simulation is explained in detail below.

The base-size in both regions has been chosen as 2mm. In addition to that the prism layer total thickness is changed from the default value of 33.33 % of the base size to 1.5mm in both automated meshing. This 1.5mm is an absolute value that corresponds to 75% of the base size but it is chosen absolute value to minimize the efforts and time needed to change it whenever a change is done to the base size.

Surface remesher it is used to improve the overall quality of existing surface and optimize it for the volume mesh models, the surface remesher can be used to retriangulate the surface. Surface remesher perform curvature refinement, proximity refinement, compatibility refinement and creates aligned meshes.

Trimmed cell mesher the trimmed cell mesher provides a robust and efficient method of producing a high-quality grid for both simple and complex mesh generation problems. It is available for both the parts-based meshing and region-based meshing approaches. Trimmer meshing model utilizes a template mesh that is constructed from hexahedral cells at the target size from which it cuts or trims the core mesh using the starting input surface. The template mesh contains refinement that is based on the local surface mesh size and local refinement controls. Growth parameters can be used to control the transitioning of mesh cell size from small to large both at the surface and far field. (SIMENS, SIMENS STAR CCM+)

Prism layer mesher the prism layer mesh model is used to generate orthogonal prismatic cells near the wall surfaces. This prism layer is defined in terms of number of prism layers, prism layer total thickness and prism layer stretching. The number of prism layers can be increased to give more accurate edges at the boundary layers. The stretching size can be adjusted to a suitable number and the prism layer total thickness can be chosen either absolute value or relative to the base size. Her in this case, it has been chosen five prism layers for both the automated mesh of domain and the automated mesh of the overset. The total thickness of the prism layer is taken as 1.5mm in both the domain and overset mesh. The rest of the default values are accepted as it is to simplify the simulation time and effort.

Hole-cutting process. The hole-cutting process is the coupling of the overset region with the background region through an overset interface. A successful coupling by use of an overset interface result in a" hole" being cut in the background mesh. In this case, it is chosen alternate hole cutting approach than layered approach because hole cutting approach is more robust for cases with close gaps.

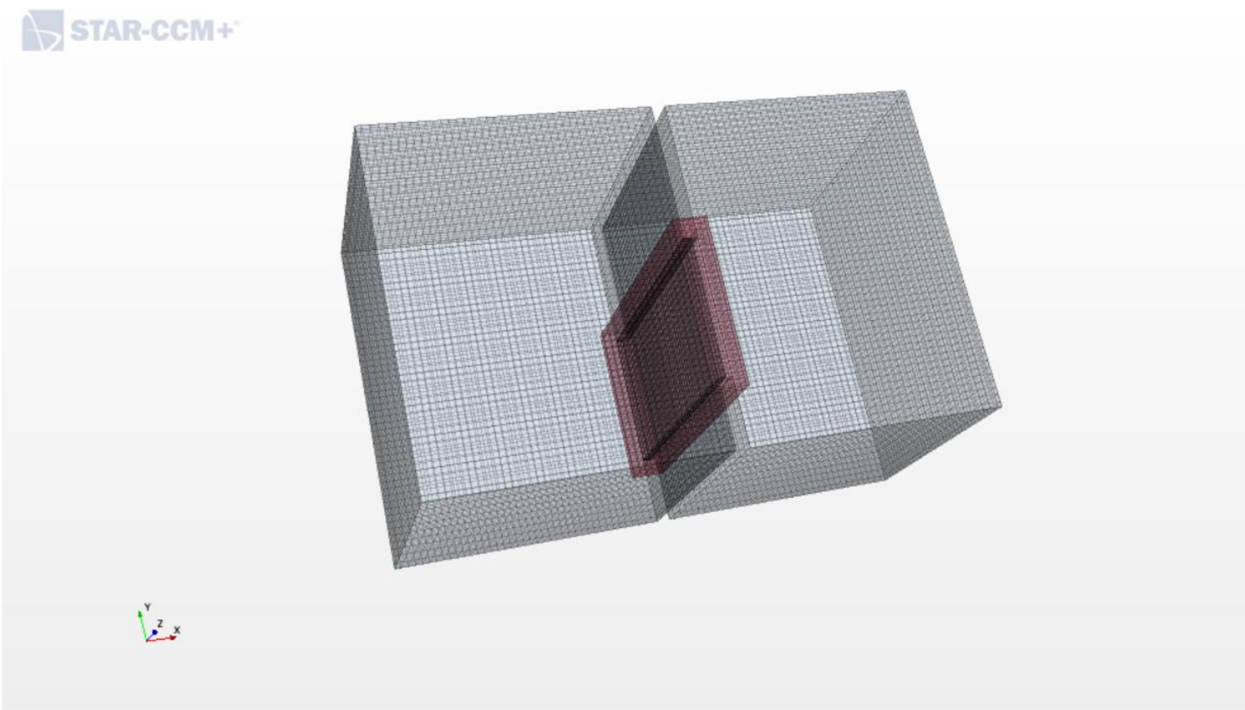

Figure 8 meshed volume of domain, overset mesh and wall.

Overset mesh zero gap.

Zerogapwall is a boundary type that is created automatically when you create an overset zero gap interface. it provides the same conditions and values as a regular wall boundary.

To create overset mesh zero gap, the two regions is selected while pressing the control key and then right click on the selected regions > go to create interface > select overset mesh zero gap interface method. The interface made can be seen by going to the interfaces that is found next to the region. alternate hole-cutting and prism layer shrinkage is selected from the properties window of the zerogap interface. The selection of the prism layer shrinkage shrunk the prism layer at the wall boundaries.

3.4 Define physics and boundary condition.

Physics continuum determines the as.

- the continuum is three-dimensional or two dimensional.
- Whether it is made up solid, liquid or gas.
- Whether its value varies with time or not (constant).

It is going to be used one physics continuum in this specific case, this physics continuum will be for the overset mesh region and domain.

The physics around the physics continuum will be as follows.

Space Three-dimensional

Time, implicit unsteady, the implicit unsteady model is the only unsteady model available with the segregated flow and segregated fluid energy models.

Material, Gas

Air is the gas type which will be used in this case, and it is the default value for the software but if somebody wants to change the value it is possible. The density of air is assumed to be constant even if it varies a little bit with the change in temperature. This constant density assumption is based on almost a constant value of temperature in the inside of most rooms, which is around 20 degrees.

Type of flow, Segregated flow. This model has its roots in constant-density flows as it is in this case.

Equation of state, constant density the equation of state in this case is constant density and this is because the medium chosen is assumed to have a constant value.

Viscous regime, laminar when the flow is assumed to have not fluctuating physical values so much both in space and time it is called laminar. In other word, it refers to a well-ordered flow that is free from macroscopic and non-repeating fluctuations. This laminar flow occurs at Reynolds number (the ratio of viscous to inertial forces) is low enough that transition to turbulence does not occur. In our case the movement of door assumed to have not given rise to non-repeating fluctuation and this assumption eases the complexity in simulation.

3.5 prepare for analysis.

In this part, the required variables are going to selected for analysis of the simulation. This depends on the needs, and to which purpose the variables is going to be used. In this case, mass exchange, energy transport, momentum transport and pollutant transport are going to be selected as a variable for analysis. The mass flow rate in kg/s is going to be visualized by drawing a derived plane on the door opening and a graph will show us how much kg/s mass is transported across this derived plane. The mass flow rate varies with the variation of door opening. The variations of this mass flow rate have different values across the opening with respect to time and this is called the transient flow of our physical value, air. the opening of door will lead to the movement of mass of air around it and this in return leads the movement of particles in the air. The movement of air can be analysed by looking at the magnitude of the speed in m/s in any point in the domain. To visualize it a derived plane can be drawn on any required place in the domain to look the variations of the speed with the movement of the door. In this case, it has been chosen a derived plane that cuts the domain horizontally (z=1) to give a good picture of the movement of the door as well as the variations of the air speed in the domain. The speed of air molecules depends on the moment applied on the door and the density of the air. It is expected to have higher value of speed when the door opens quicker and faster and lower values of speed when it the door opens with a lower angular speed. The analysis is going to look if this expectation is true and find out at which instant of time does the door pushes a huge amount of air and how the walls, floor, roof is affected by the speed of air. The size of door opening is assumed around 90 grader and this value is chosen to be closer to real door opening.
In the process of analysis, the speed of door is set to different values to analyse how this difference of door speed affects the air speed in return affects the indoor air condition.

The different angular speed of the door is shown below. To simplify the simulating, it is chosen around three different angular speeds of the door. The simulation is faster at high angular speed and slower at low angular speed, so it is going to take much time to simulate the simulation with 1.5 angular velocity.

Simulation order	**Angular door speed (rad/s)**	**Time taken for the door to accomplish one cycle (s)**
First	15	0.2
Second	5	0.6
Third	1.5	2

Table 1 door angular speed versus time takes per cycle.

It has been chosen that the domain and the overset regions is meshed to a value of base size 2mm. as it has been mentioned earlier the interaction is between the domain and the overset mesh surrounding the door. Due to very narrow gap between the door and the domain it is chosen to simulate with zero gap overset mesh instead of the normal overset mesh. So, in our case, some part of overset mesh is outside the domain.

As it is mentioned in the table 1 above, it will be using the door angular velocities one by one to analyse how the result of the simulation is going to differ. Three simulations are going to be explained around three opening states, at the start of opening, at maximum opened state and at closed state. Let us start putting the first row from the table 1 in STAR CCM+ to run our first simulation.

First simulation (angular door velocity = 15 rad/s and time taken per cycle 0.2s)

`($Time<=0.1) ? 15 : (($Time>0.1 && $Time<0.2) ? -15 : 0.0)` Equation 3.3

Angular velocity is 15rad/s for every time less or equal to 0.1s and -15rad/s for every time between 0.1 and 0.2 and the velocity will zero for every other time than the ones mentioned in the above.

Second simulation (angular door velocity = 5 rad/s and time taken per cycle 0.6s)

`($Time<=0.3) ? 5 : (($Time>0.3 && $Time<0.6) ? -5 : 0.0)` Equation 3.4

Angular velocity is 5rad/s for every time less or equal to 0.3s and -15rad/s for every time between 0.3 and 0.6 and the velocity will zero for every other time than the ones mentioned in the above.

Third simulation (angular door velocity = 1.5 rad/s and time taken per cycle 2s)

`($Time<=1) ? 1.5 : (($Time>1 && $Time<2) ? -1.5 : 0.0)` Equation 3.5

Angular velocity is 1.5rad/s for every time less or equal to 1s and -15rad/s for every time between 1 and 2 and the velocity will zero for every other time than the ones mentioned in the above.

3.6 Run simulation

After the simulation is ready to the final step, running the simulation. One must remember initializing the physics variables before running the simulation in order the variables to start from the reliable initial value. While the running process is continuing, it is possible to look at if the simulation is converging or not. The simulation is converging well if it converges to value times the power of -4 and it should not always give this value to say it converges very well but it should give a value around that and it is also possible to set stopping criteria for the simulation to stop. After the satisfactory converging value has been achieved, the simulation can be analyzed to give as a required result.

4. Results and Discussion.

First simulation (angular door velocity = 15 rad/s and time taken per cycle 0.2s)

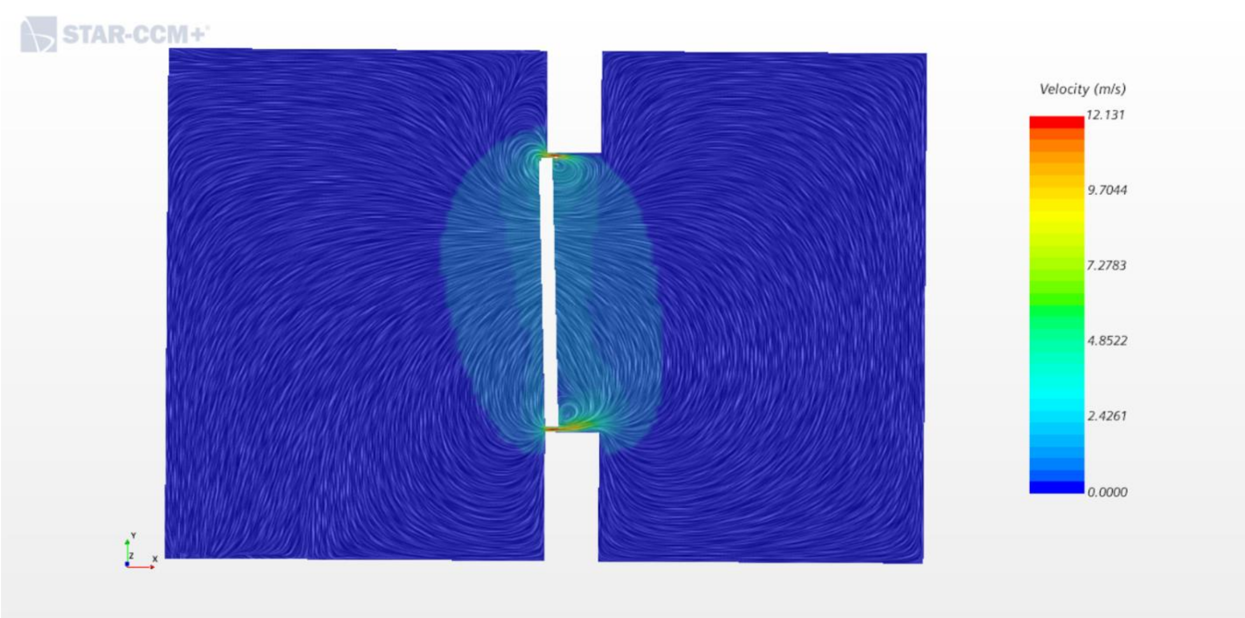

Figure 9 vector scene at the time of door opening for the first simulation ($\theta = 15\text{rad/s}$, time taken =0.2).

Before the door is set to move the only air movement was through the small gap between the door and side walls, roof, and floor but this amount of air is very small in amount in such a way that its effect is negligible.

When the door starts to open, it pushes air around it and gives rise to a certain air velocity. In this vector scene its magnitude as well as direction is clearly shown to give a good understanding how the movement is happening. The velocity seems to have a little higher value at the start of door opening and then it decreases gradually as the door starts to open more and more. As we see on figure 9 above, the velocity spectra have dense green in colour (around 7m/s) at the tips of the door and less dense (around 5m/s) around the other body of the door. This difference of velocities around the door is due to the gap between the door and the wall gives rise to a little more velocity difference than the rest part around the door. As it is mentioned in the above the velocity starts to decrease gradually from higher value and we are going to see if this decrement is holding by looking up on the next figure on which the door is fully opened. As we see from the figure 9 above the velocities shown is far higher than normal air velocity inside a room this is because of the high angular velocity of the door that gives rise to such high velocities. This high angular velocity is selected to see how its effect is going to be but in real life, movement of normal door does not have such high angular velocity. Scalar scene of at the start of door opening can be seen in appendix A figure 24.

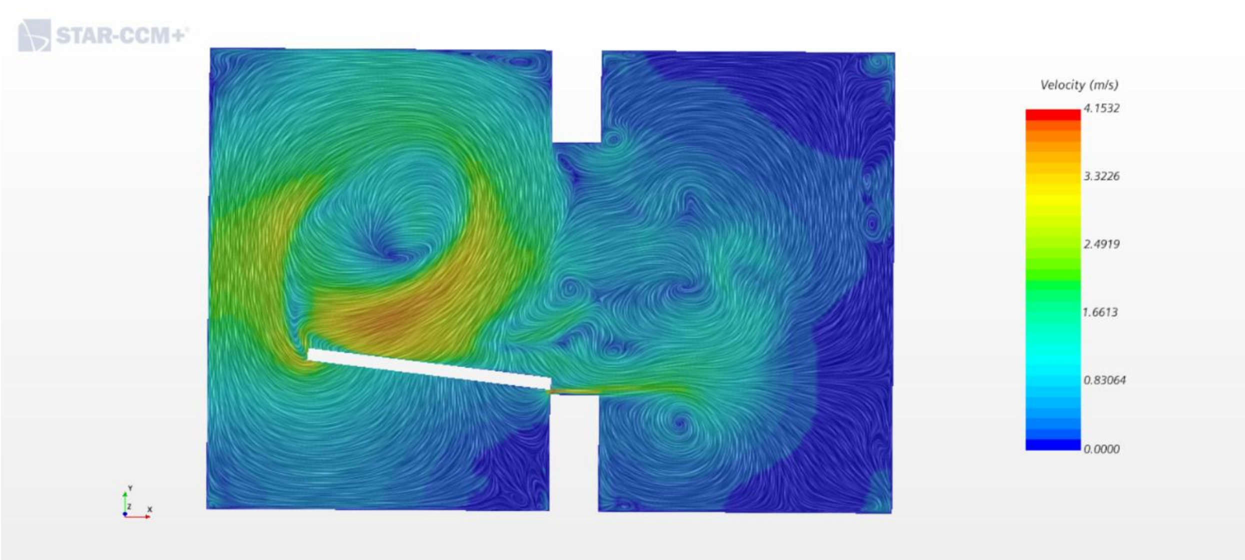

Figure 10 vector scene at the turning point when the door is fully opened for the first simulation ($\theta = 15\text{rad}/s$, time taken =0.2).

As we see from the figure 10 above the door is in fully opened state, at this point the air around the door has much lower velocity spectra comparing to when the door was at the star of opening. This reduced speed shows us the air has calmed a little bit down from its highest value to a velocity around 2m/s even if there were some fluctuations in its way to this state. Looking in the figure 10 above, it can also be seen that the velocity spectra on the door openings sides volume is higher than the ones on the opposite volume. This difference in speed in the two room volumes is due to the movement of the door. As we see the door has more effect on the air around it than the air far away from it and this more effect leads to more velocity spectra on the air around the door. After this state, the movement of the door is changing direction from positive to negative angular velocity and in return gives a little higher velocity right after this turning point. Again, the speed calms down further as it going to ward it closed state as it will be shown in the figure down when it is on its final closed state. As we see from the figure 10 above the velocities shown is far higher than normal air velocity inside a room this is because of the high angular velocity of the door that gives rise to such high velocities. This high angular velocity is selected to see how its effect is going to be but in real life, movement of normal door does not have such high angular velocity. Scalar scene of at the door returning instant can be seen in appendix A figure 25.

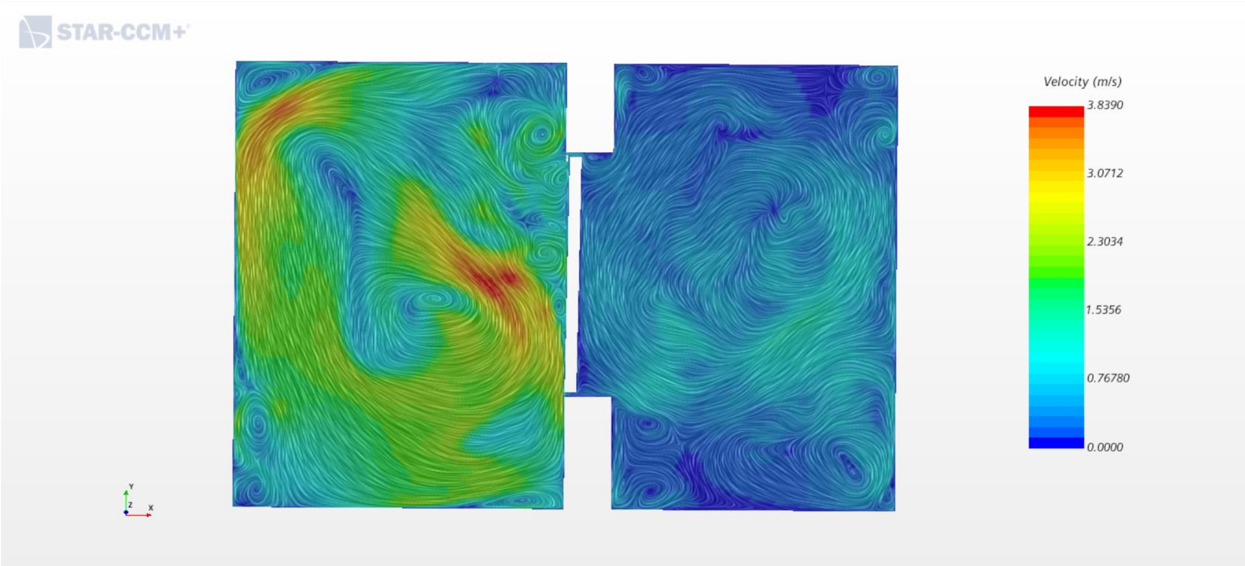

Figure 11 vector scene at the end of rotation when the door is in the closed mode for the first simulation ($\theta = 15\mathrm{rad}/s$, time taken =0.2).

After the door is set to a closed state the only air movement was through the small gap between the door and side walls, roof, and floor but this amount of air is very small in amount in such a way that its effect is negligible. In this vector scene its magnitude as well as direction is clearly shown to give a good understanding how the movement of air is happening.

Her in this figure 11 hinged door is in the final state of rest (v=0) and at this state it can be seen most part of the volume in the right side of the door seems to have a velocity around 1m/s but in contrast to that most of the volume in the left side of the door has air velocity as double as the part of volume in the right. The room on side of door opening seem to end up with double higher velocities than the other rom. The air velocities take a little time to calm to its lowest required level even if the door is at fully closed state this is due to some kinetic energy is still stored tin the air particles that helps the particle to move a little longer. As we see from the figure 11 above the velocities shown is fur higher than normal air velocity inside a room this is because of the high angular velocity of the door that gives rise to such high velocities. This high angular velocity is selected to see how its effect is going to be but, movement of normal door does not have such high angular velocity. Scalar scene of at the instant when the door fully closed can be seen in appendix A figure 26.

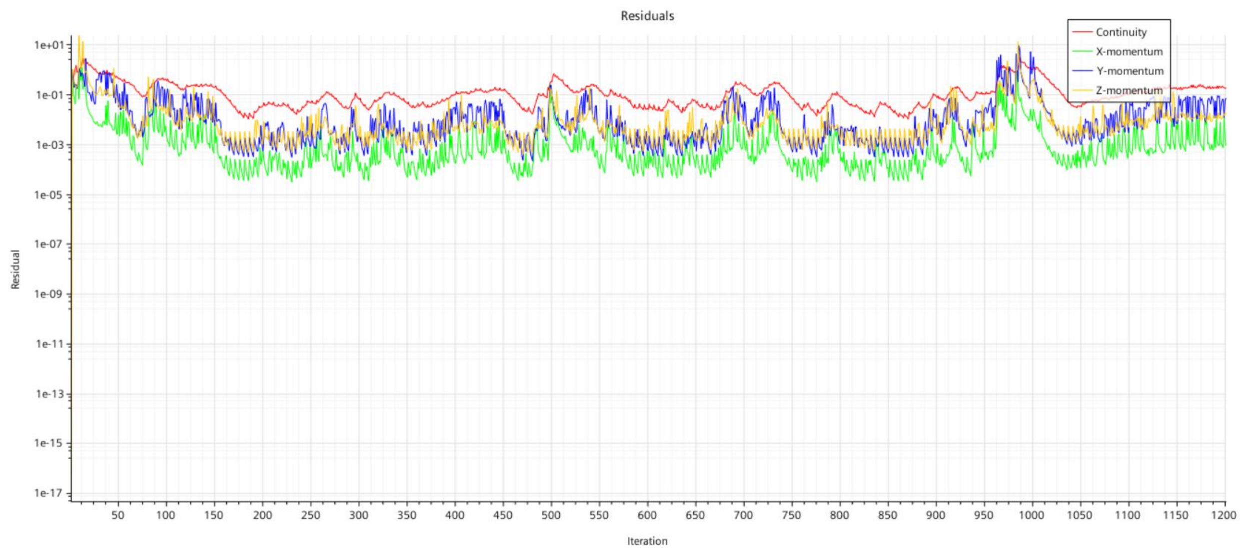

Figure 12 residuals versus iteration for the first simulation ($\theta = 15\text{rad}/s$, time taken =0.2).

The figure 12 above shows how the residuals of momentum (x-component, y-component, z-component) and continuity is converging. This simulation is for a flow that is time-dependent therefore convergence must occur within each time-step, and it can be seen clearly from the figure that the residuals has converged many times through the cycle. “If the simulation is steady state, the convergence is displayed over the total number of iterations. If the solution is time-dependent, make sure that convergence occurs within each time-step.” (SIMENS, Simsenter STAR CCM+, u.d.). As it is seen from figure 12 it is clearly can markers that the convergence happens with each time-step through the whole simulation period. This result of simulation is agreed to the statement given in the guide of STAR CCM+ and it shows that our simulation gives us good result.

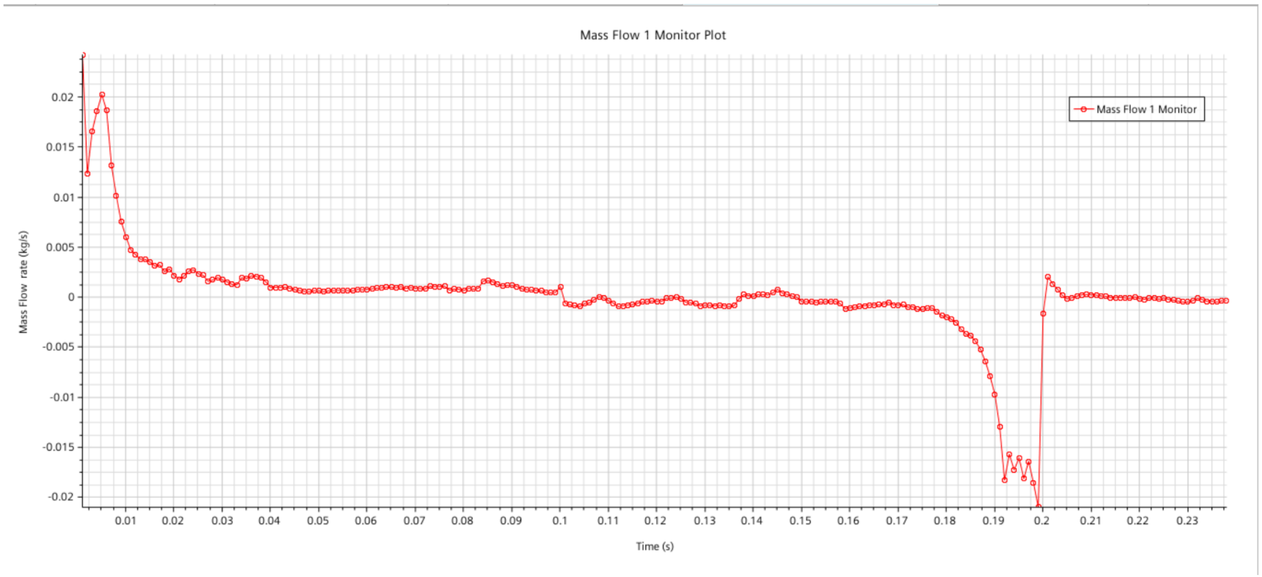

Figure 13 mass flow rate in kg/s versus time(s) for the first simulation ($\theta = 15\text{rad}/s$, time taken =0.2).

The figure 13 above shows the variation of mass flow rate across the door opening with time. Right after the door opening the mass flow rate sinks down to a value around zero kg/s and stays there until the door comes closer to the closed state. Even if there are some fluctuations at the door returning point, it is more evident around the door opening and closing. At the closed state, mass flow rate sinks furthermore but in this case to toward negative values. This negative value shows that mass flow rate changes its direction and starts to flow opposite the flow that happens when door starts to open. Finally mass flow rate again comes back to around zero values after the door closes fully. It can be concluded that the mass flow rate changes at the instant the door changes state, it can be from the closed state to open or from open stat to closed.

Second simulation (angular door velocity = 5 rad/s and time taken per cycle 0.6s)

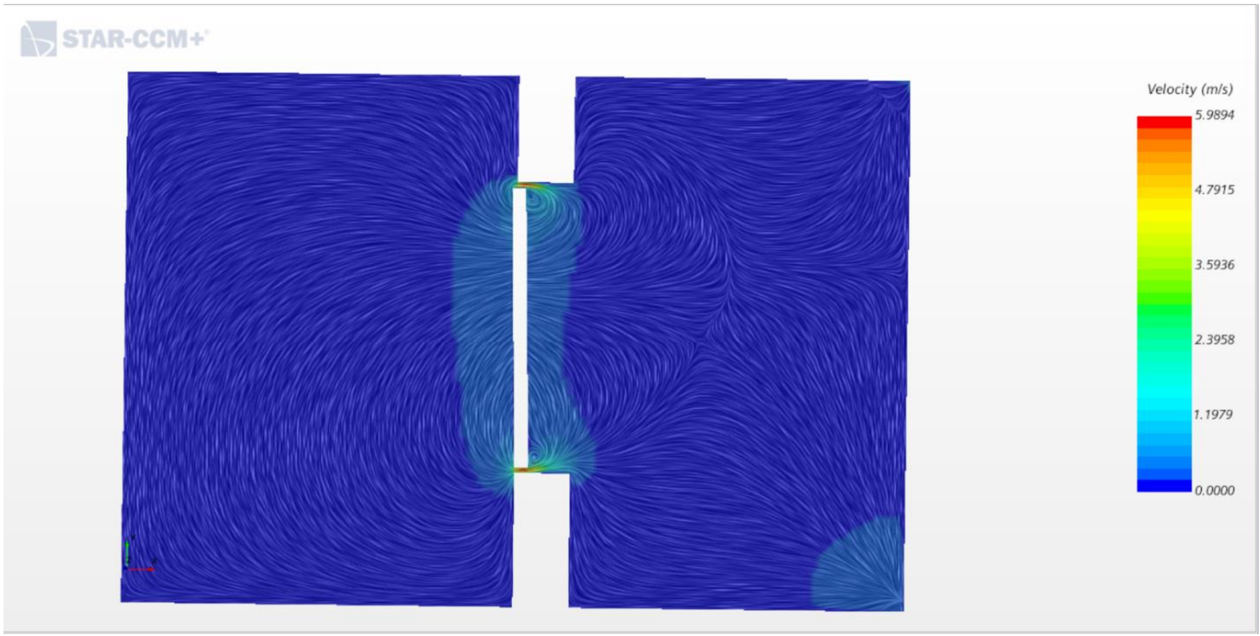

Figure 14 vector scene at the start time of door opening for the second simulation ($\theta = 5\mathrm{rad/s}$, time taken =0.6).

Before the door is set to move the only air movement was through the small gap between the door and side walls, roof, and floor but this amount of air is very small in amount in such a way that its effect is negligible.

When the door starts to open, it pushes air around it and gives rise to a certain air velocity. In this vector scene its magnitude as well as direction is clearly shown to give a good understanding how the movement is happening. The velocity seems to have a little higher value at the start of door opening and then it decreases gradually as the door starts to open more and more. As we see on figure 14 above, the velocity spectra have dense green in colour (around 2.5 m/s) at the tips of the door and less dense (around 2 m/s) around the other body of the door. This difference of velocities around the door is due to the gap between the door and the wall gives rise to a little more velocity difference than the rest part around the door. Comparing this instant of simulation with the same instant on the simulation above that has higher angular velocity, the air velocities is much lower than the ones with higher angular velocity. At door opening in the first simulation the velocity spectra are between 5 and 7m/s whereas the velocity in this simulation is between 2.5 and 2m/s and this value shows us the velocity spectra is directly proportional with the angular velocity. As it is mentioned in the above the velocity starts to decrease gradually from higher value and we are going to see if this decrement is holding by looking up on the next figure on which the door is fully opened. Scalar scene of at the time of door opening can be seen in appendix A figure 27.

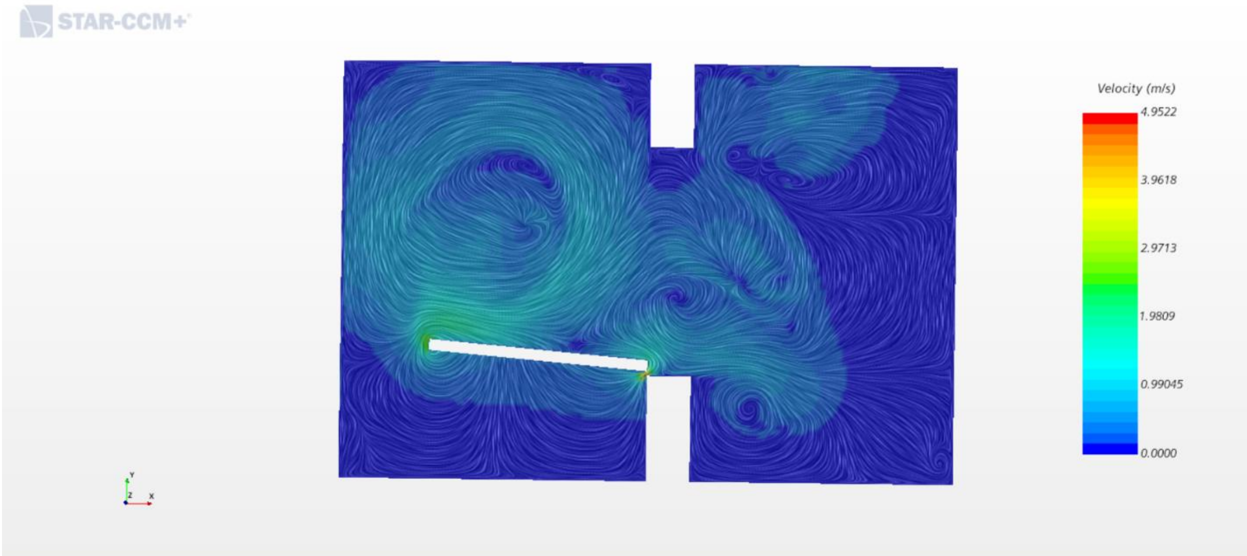

Figure 15 vector scene at the turning point when door fully opened for the second simulation ($\theta = 5\mathrm{rad/s}$, time taken =0.6).

As we see from the figure 15 above the door is in fully opened state, at this point the air around the door has much lower velocity spectra comparing to when the door was at the star of opening. This reduced speed shows us the air has calmed a little bit down from its highest value to a velocity around 2m/s even if there were some fluctuations in its way to this state. Looking in the figure 15 above, it can also be seen that the velocity spectra on the door openings sides volume is higher than the ones on the opposite volume. This difference in speed in the two room volumes is due to the movement of the door. As we see the door has more effect on the air around it than the air far away from it and this more effect leads to more velocity spectra on the air around the door. After this state, the movement of the door is changing direction from positive to negative angular velocity and in return gives a little higher velocity right after this turning point. Again, the speed calms down further as it going to ward it closed state as it will be shown in the figure down when it is on its final closed state. Comparing this instant of simulation with the same instant on the simulation above that has higher angular velocity, the air velocities is much lower than the ones with higher angular velocity. At the instant when the door fully opened, in the first simulation the velocity spectra are between 1.5 and 2.5m/s whereas the velocity in this simulation is between 1 and 2m/s and this value shows us the velocity spectra is directly proportional with the angular velocity. Scalar scene of at the returning point of the door can be seen in appendix A figure 28.

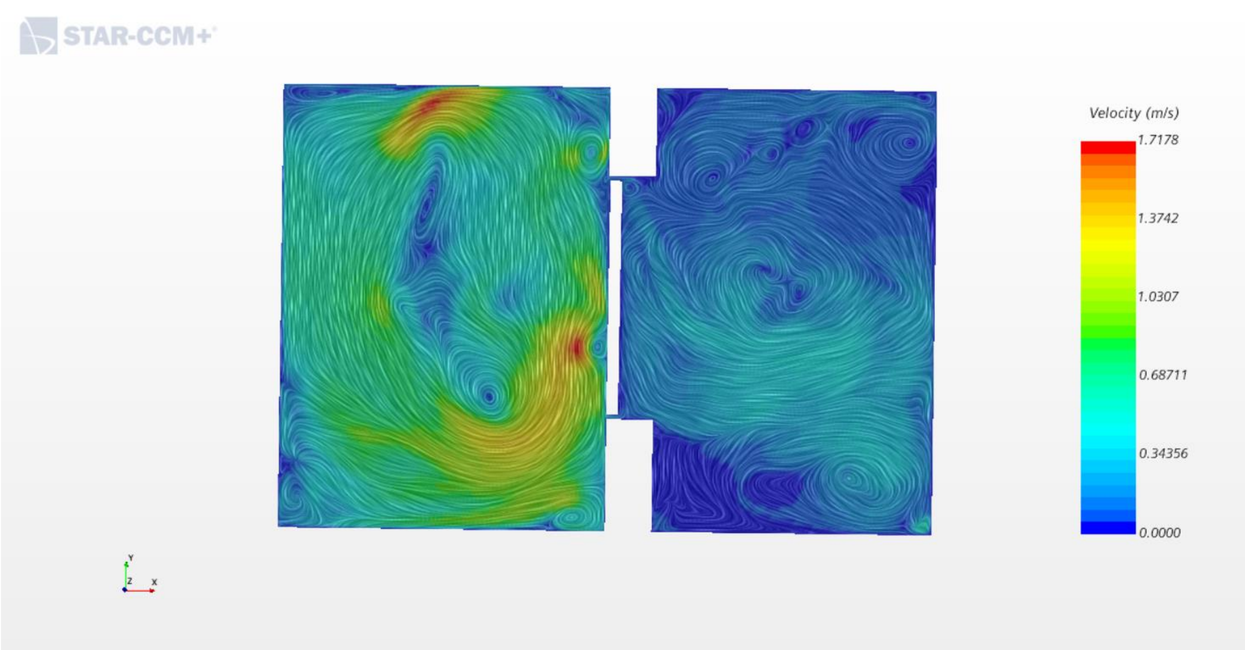

Figure 16 vector scene at the end of rotation when door is in the closed mode for the second simulation ($\theta = 5\mathrm{rad}/s$, time taken =0.6).

After the door is set to a closed state the only air movement was through the small gap between the door and side walls, roof, and floor but this amount of air is very small in amount in such a way that its effect is negligible. In this vector scene its magnitude as well as direction is clearly shown to give a good understanding how the movement is happening.

Her in this figure 16 hinged door is in the final state of rest (v=0) and at this state it can be seen most part of the volume in the right side of the door seems to have a velocity around 1m/s but in contrast to that most of the volume in the left side of the door has air velocity as double as the part of volume in the right. The room on side of door opening seem to end up with double higher velocities than the other rom. The air velocities take a little time to calm to its lowest required level even if the door is at fully closed state this is due to some kinetic energy is still stored tin the air particles that helps the particle to move a little longer. As we see from the figure 16 above the velocities shown is far higher than normal air velocity inside a room this is because of the high angular velocity of the door that gives rise to such high velocities. This high angular velocity is selected to see how its effect is going to be but, movement of normal door does not have such high angular velocity. Scalar scene when the door is fully closed can be seen in appendix A figure 29.

Figure 17 residuals versus iteration for the second simulation ($\theta = 5\mathrm{rad/s}$, time taken =0.6).

The figure 17 above shows how the residuals of momentum (x-component, y-component, z-component) and continuity is converging. This simulation is for a flow that is time-dependent therefore convergence must occur within each time-step, and it can be seen clearly from the figure that the residuals has converged many times through the cycle. “If the simulation is steady state, the convergence is displayed over the total number of iterations. If the solution is time-dependent, make sure that convergence occurs within each time-step.” (SIMENS, Simsenter STAR CCM+, u.d.)

As it is seen from figure 17 it is clearly can markers that the convergence happens with each time-step through the whole simulation period. This result of simulation is agreed to the statement given in the guide of STAR CCM+ and it shows that our simulation gives us good result.

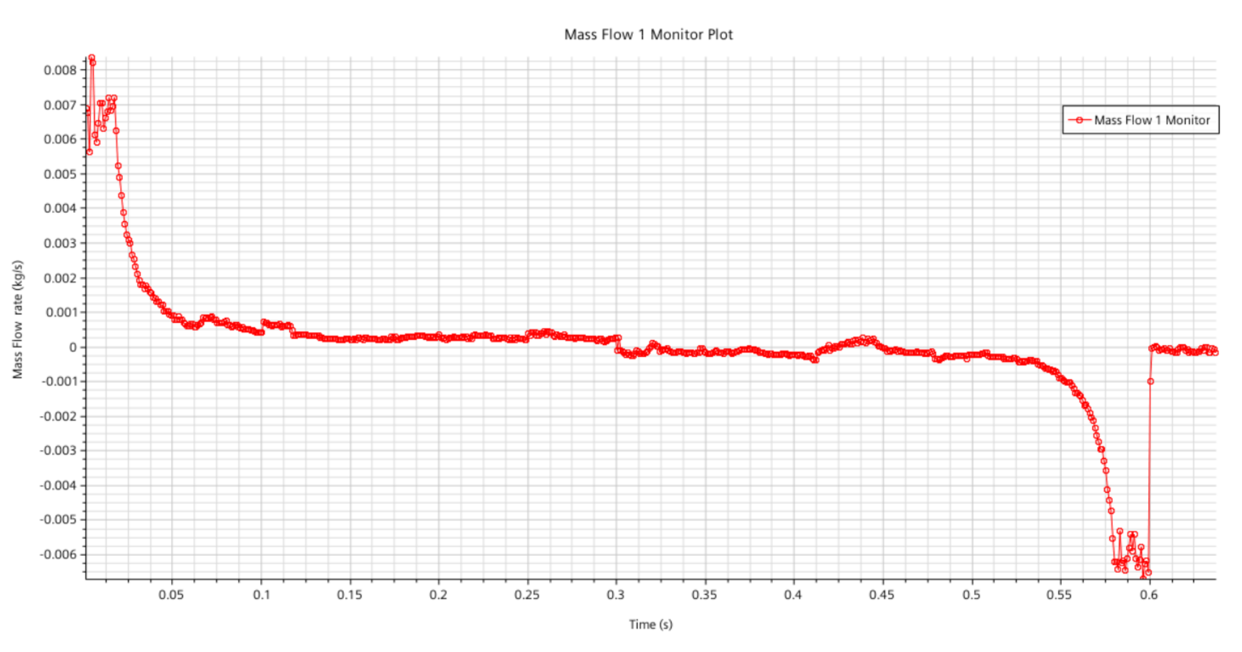

Figure 18 mass flow rate (kg/s) versus time (s) for the second simulation ($\theta = 5\text{rad/s}$, time taken =0.6).

The figure 18 above shows the variation of mass flow rate across the door opening with time. Right after the door opening the mass flow rate sinks down to a value around zero kg/s and stays there until the door comes closer to the closed state. Around the closed state mass flow rate sinks furthermore but currently to its negative values. This negative value shows that mass flow rate changes direction and starts to flow opposite the flow that happens when door starts to open. Finally mass flow rate again comes back to around zero values after the door closes fully. As we see from the figure mass flow rate changes at the instant the door changes state, it can be from the closed state to open or from open stat to closed. The detailed data of the figure 18 is listed in table and this can be seen in appendix B.

Third simulation (angular door velocity = 1.5 rad/s and time taken per cycle 2s)

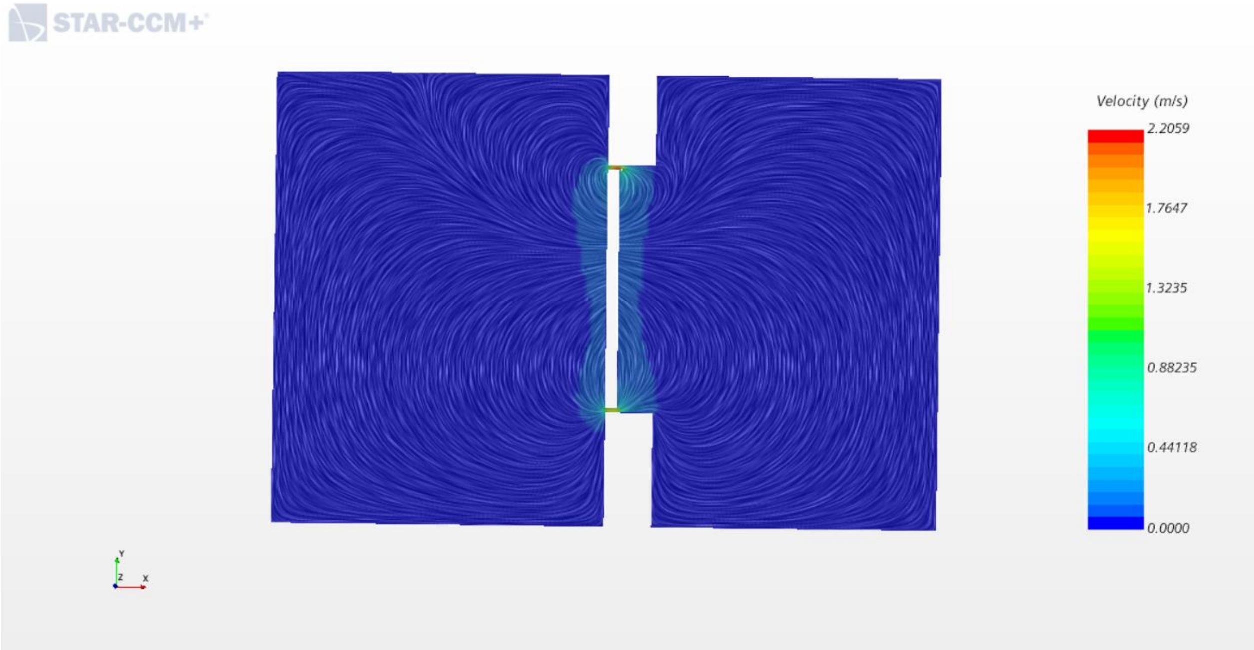

Figure 19 vector scene at the start time of door opening for the third simulation ($\theta = 1.5$ rad/s , time taken =2).

Before the door is set to move the only air movement was through the small gap between the door and side walls, roof, and floor but this amount of air is very small in amount in such a way that its effect is negligible.

When the door starts to open, it pushes air around it and gives rise to a certain air velocity. In this vector scene its magnitude as well as direction is clearly shown to give a good understanding how the movement is happening. The velocity seems to have a little higher value at the start of door opening and then it decreases gradually as the door starts to open more and more. As we see on figure 19 above, the velocity spectra have dense green in colour (around 0.8 m/s) at the tips of the door and less dense (around 0.5m/s) around the other body of the door. This difference of velocities around the door is due to the gap between the door and the wall gives rise to a little more velocity difference than the rest part around the door. Comparing this instant of simulation with the same instant on the simulation above that has higher angular velocity, the air velocities is much lower than the ones with higher angular velocity. At door opening in the second simulation the velocity spectra are between 2 and 2.5m/s whereas the velocity in this simulation is between 0.5 and 0.8m/s and this value shows us the velocity spectra is directly proportional with the angular velocity. As it is mentioned in the above the velocity starts to decrease gradually from higher value and we are going to see if this decrement is holding by looking up on the next figure on which the door is fully opened. Scalar scene of at the start of door opening can be seen in appendix A figure 30.

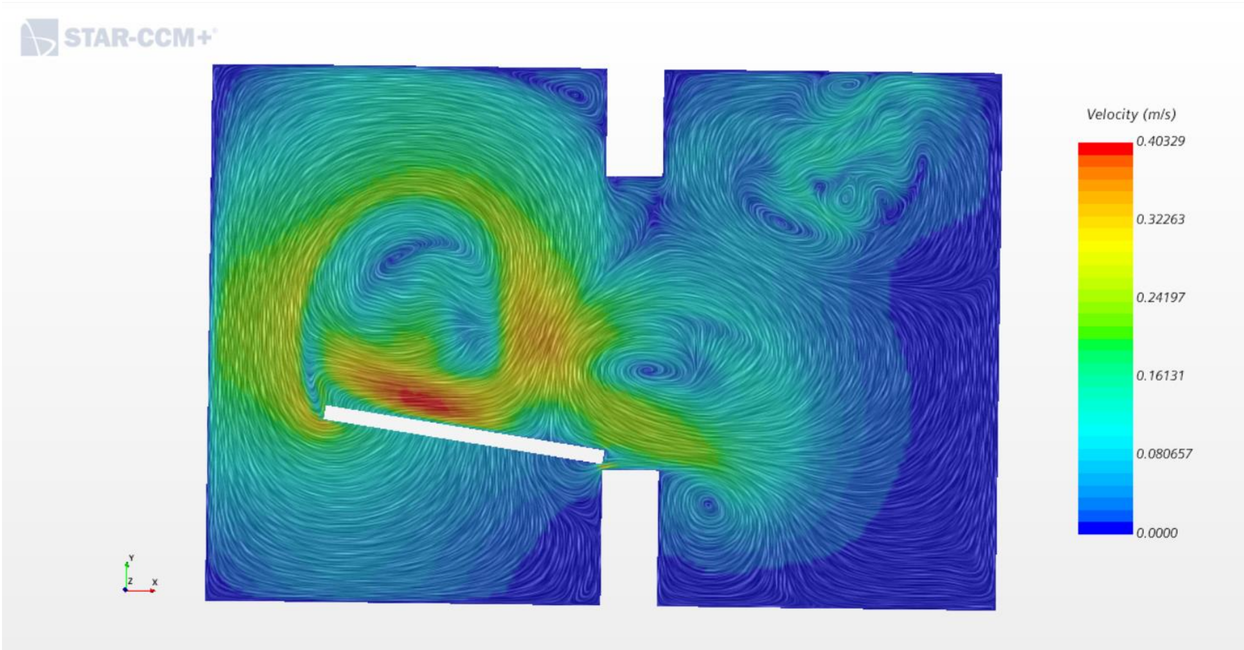

Figure 20 vector scene at the time when the door fully opened for the third simulation ($\theta = 1.5\ \mathrm{rad}/s$, time taken =2).

As we see from the figure 20 above the door is in fully opened state, at this point the air around the door has much lower velocity spectra comparing to when the door was at the star of opening. This reduced speed shows us the air has calmed a little bit down from its highest value to a velocity around 0.2 m/s even if there were some fluctuations in its way to this state. Looking in the figure 20 above, it can also be seen that the velocity spectra on the door openings sides volume is higher than the ones on the opposite volume. This difference in speed in the two room volumes is due to the movement of the door. As we see the door has more effect on the air around it than the air far away from it and this more effect leads to more velocity spectra on the air around the door. After this state, the movement of the door is changing direction from positive to negative angular velocity and in return gives a little higher velocity right after this turning point. Comparing this instant of simulation with the same instant on the simulation above that has higher angular velocity, the air velocities is much lower than the ones with higher angular velocity. At the instant of fully opened state in the second simulation the velocity spectra are between 1.5 and 2.5m/s whereas the velocity in this simulation is between 0.15 and 0.25m/s and this value shows us the velocity spectra is directly proportional with the angular velocity. Again, the speed calms down further as it going to ward it closed state as it will be shown in the figure down when it is on its final closed state. Scalar scene of at the door returning instant can be seen in appendix A figure 31.

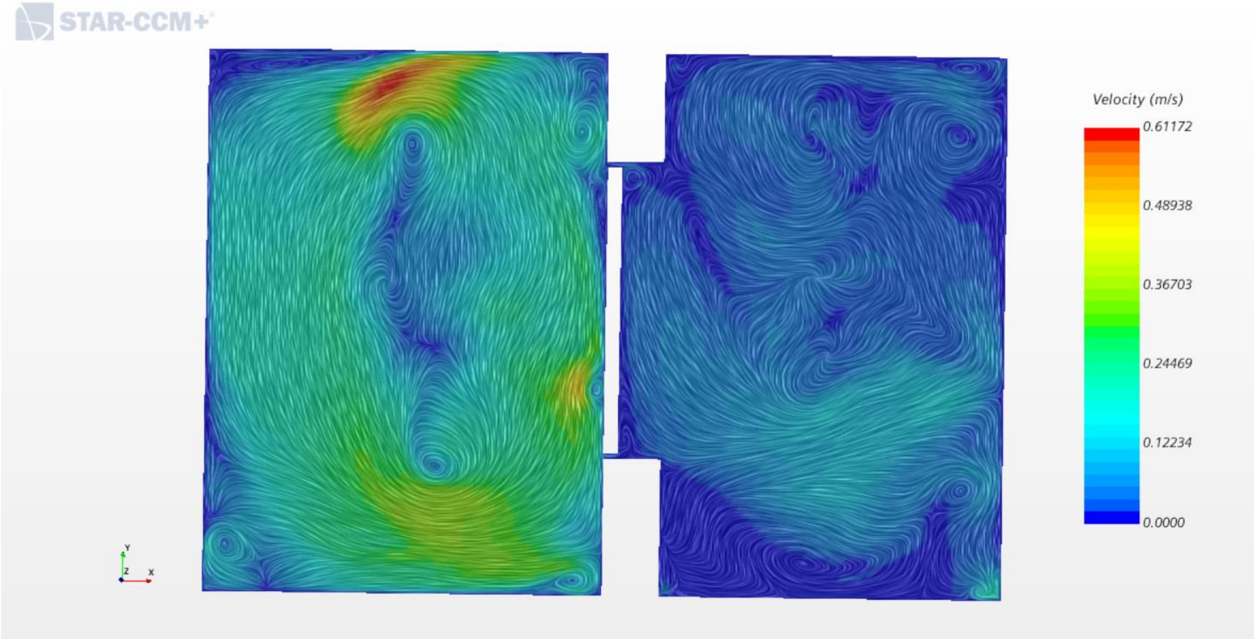

Figure 21 vector scene at the time when the door fully closed state for the third simulation ($\theta = 1.5\ \mathrm{rad/s}$, time taken =2).

Her in this figure 21 hinged door is in the final state of rest (v=0) and at this state it can be seen most part of the volume in the right side of the door seems to have a velocity around 0125 m/s but in contrast to that most of the volume in the left side of the door has air velocity as double as the part of volume in the right. The room on the side of door opening seem to end up with double higher velocities than the other rom. The air velocities take a little time to calm to its lowest required level even if the door is at fully closed state this is due to some kinetic energy is still stored tin the air particles that helps the particle to move a little longer. As we see from the figure 21 above the velocities shown is almost around normal air velocity inside a room this is because of the reliable angular velocity of the door that gives rise to such normal and acceptable velocities. This high angular velocity is selected as out best option out from the two other simulations. Comparing this instant of simulation with the same instant on the simulation above that has higher angular velocity, the air velocities is much lower than the ones with higher angular velocity. At instant when the door closed fully in the second simulation the velocity spectra are between 0.5 and 1m/s whereas the velocity in this simulation is between 0.125 and 0.25 m/s and this value shows us the velocity spectra is directly proportional with the angular velocity. Scalar scene of at the instant when the door fully closed can be seen in appendix A figure 32.

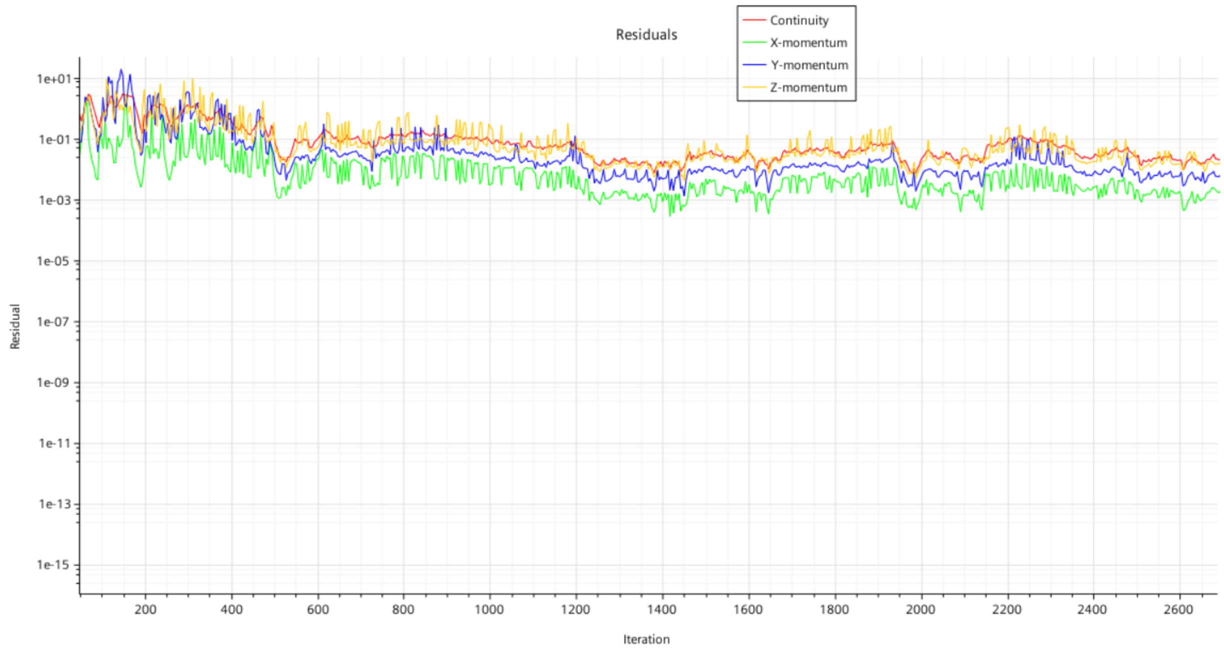

Figure 22 residuals versus iteration for the third simulation ($\theta = 1.5 rad/s$, time taken =2).

The figure 22 above shows how the residuals of momentum (x-component, y-component, z-component) and continuity is converging. This simulation is for a flow that is time-dependent therefore convergence must occur within each time-step, and it can be seen clearly from the figure that the residuals has converged many times through the cycle. “If the simulation is steady state, the convergence is displayed over the total number of iterations. If the solution is time-dependent, make sure that convergence occurs within each time-step.” (SIMENS, Simsenter STAR CCM+, u.d.)

As it is seen from figure 22 it is clearly can markers that the convergence happens with each time-step through the whole simulation period. This result of simulation is agreed to the statement given in the guide of STAR CCM+ and it shows that our simulation gives us good result.

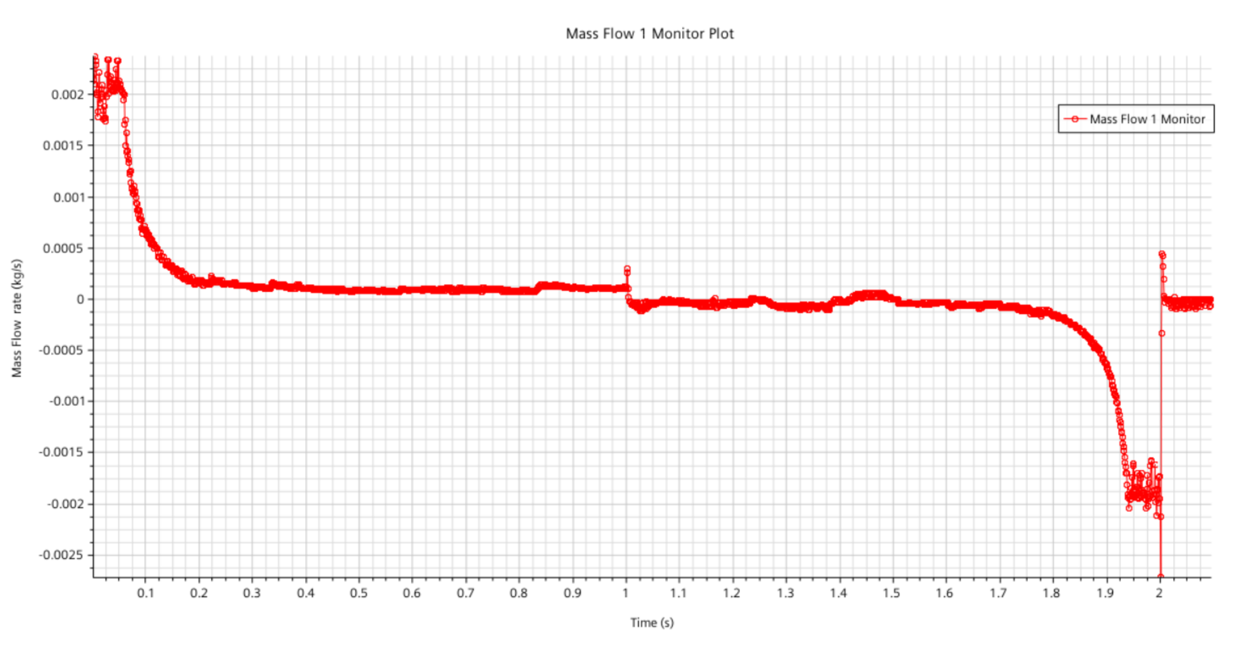

Figure 23 mass flow rate (kg/s) versus time (s) for the third simulation ($\theta = 1.5 rad/s$, time taken =2).

The figure 23 above shows the variation of mass flow rate across the door opening with time. Right after the door opening the mass flow rate sinks down to a value around zero kg/s and stays there until the door comes closer to the closed state. Even if there are some fluctuations at the door returning point, it is more evident around the door opening and closing. At the closed state, mass flow rate sinks furthermore but in this case to toward negative values. This negative value shows that mass flow rate changes its direction and starts to flow opposite the flow that happens when door starts to open. Finally mass flow rate again comes back to around zero values after the door closes fully. It can be concluded that the mass flow rate changes at the instant the door changes state, it can be from the closed state to open or from open stat to closed. The detailed data of the figure 23 is listed in table and this can be seen in appendix B.

5. Conclusions

In the first part of this paper, the theoretical background is described to show how the software is been built. Mass equation, moment equation, energy equation, transport equation and equation of state is some of the core in theoretical background. Turbulence equation and its models is also explained in detail as part of basic background toward giving good understanding of CFD methods. Applying filtering or filtering functions on unsteady Naiver-strokes equations to separate large eddy from small eddies and Scale resolving simulations via detached eddy simulations (DES) and its variants (modification of RANS model) is covered as a theory part in this paper.

The second and most important part of this work will be the usage of overset mesh zero gap for moving rigid boundaries. This work is also very relevant to the present pandemic situation. As it mentioned above our main aim of this paperwork is to simulate hinged door and analyse the variation of the flow properties. Due to the variations of the flow properties with time and space transient flow analysis is used to get the solution. Hinged door is located between two rooms that has different initial flow properties, but it will be assumed to have the same initial properties to simplify the simulations time and effort. The door opens at a certain angular velocity and its effect up on the air around the door is visualized to analyze the data. In this case, mass flow, air velocities, transfer of energy in the form momentum is analyzed from the result of the simulation. The geometry of the domain to be simulated is created in STAR CCM+ and the created geometry is simulated in the simulation itself. The movement of the door is made to move a certain angle before it returns to its initial state of rest, and this is done by creating a suitable function that governs the motion of the door. The speed of the door can be adjusted in the function that has been created in to compare the results of simulation that simulated with different angular velocities. Screen shot of results at three different states, at the start of door opening, when the door opens fully, and when the door finally closed. In addition to that the mass flow is traced by creating a derived plane in the door opening and the results is shown in kg/s versus time. has been taken to show and compare the results to each other. This door opening as well as the movement of fluid from one room to the other will be simulated in a computer by software that use CFD method. The most known and well used software that used in this purpose is Star CCM+. After we have simulated the three simulations that has different angular velocities, the result shows that the simulation with lowest angular velocity gives rise to lower air velocity spectra. In the third simulation that has done, the angular velocity of the hinged door is 1.5rad/s and this results to air velocity spectra around 0.15m/s. The third simulation is the only simulation that results in a velocity spectrum that give good indoor air condition and out of this it can be concluded that it is important to have lower angular velocity to have comfortable air movement. In addition to that the side of door opening is also important this is shown clearly in the three simulations. The side on the door opening shows always a little higher air velocities than the room or volume opposite to the opening of the door.

6. References

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Appendices

Appendix A

Appendix B

Angular velocity = 15rad/s		**Angular velocity = 1.5rad/s**	
Physical Time (s)	Mass Flow Rate (kg/s)	Physical Time (s)	Mass Flow rate (kg/s)
0.001	0.0197435701661173	0.001	0.002140578977302454
0.002	0.0133446728104779	0.002	0.0021963458492622384
0.003	0.0115276826962346	0.003	0.0020972988946052215
0.004	0.00552391962445073	0.004	0.0023697843937863896
0.005	0.00318465368263152	0.005	0.002328795121473166
0.006	0.0034139238763175	0.006	0.002277815372849936
0.007	0.00261190852667352	0.007	0.0019894367547581785
0.008	-0.000938689847051596	0.008	0.002010781213015676
0.009	0.000330135524782443	0.009000000000000001	0.001777716207121681
0.01	0.00290061773248017	0.010000000000000002	0.0018221097324845994
0.011	0.00169329290841355	0.011000000000000003	0.002046160851000272
0.012	0.00166716882297924	0.012000000000000004	0.0022054409210503297
0.013	0.000727768943312397	0.013000000000000005	0.0019144561928521131
0.014	0.000524749881811043	0.014000000000000005	0.0019093360439703783
0.015	0.000131088036544795	0.015000000000000006	0.001999557050601765
0.016	0.00147939612046904	0.016000000000000007	0.0020430659105182274
0.017	0.00051684156720282	0.017000000000000008	0.0020905589163268297
0.018	0.000185158501394011	0.01800000000000001	0.001970956614137833
0.019	-1.30416684987324e-05	0.01900000000000001	0.0018347924294579007
0.02	0.000202423943562321	0.02000000000000001	0.0017540679766316644
0.021	0.000553075654824176	0.02100000000000001	0.001875229815013084
0.022	0.000944029121514012	0.022000000000000013	0.0017680300553229145
0.023	0.000979871446590784	0.023000000000000013	0.0017620142481945213
0.024	0.000577292429277245	0.024000000000000014	0.0017375837705858551
0.025	0.00108281214692597	0.025000000000000015	0.001973592100190649
0.026	0.00088222466723137	0.026000000000000016	0.0020335692296988965
0.027	0.000770804366446887	0.027000000000000017	0.0021892386311031927
0.028	0.000552257610514622	0.028000000000000018	0.0023385280048182234
0.029	0.000438181040052302	0.02900000000000002	0.0020015319972688265
0.03	6.78060256060316e-05	0.03000000000000002	0.002332388825578682
0.031	0.000834417568466038	0.03100000000000002	0.0020772821005391774
0.032	0.000879910453554744	0.03200000000000002	0.002149775746265259
0.033	0.00057881397317275	0.03300000000000002	0.00211701017836276
0.034	0.000547262869299568	0.03400000000000002	0.0021670271479034666

0.035	0.000331724560143165	0.035000000000000024	0.0020358515935102795
0.036	0.000438130900083778	0.036000000000000025	0.00204650058183086
0.037	0.000375460881745252	0.037000000000000026	0.002029152405108037
0.038	0.000555317426849766	0.03800000000000003	0.002025603164366916
0.039	0.000481526385124631	0.03900000000000003	0.0021371419168865237
0.04	0.000185024241534417	0.04000000000000003	0.002021787150012547
0.041	0.000214585698934362	0.04100000000000003	0.0021349937616053647
0.042	0.000196224451786911	0.04200000000000003	0.002067885040663551
0.043	0.00037587774082483	0.04300000000000003	0.002243295825264569
0.044	0.000666521384710932	0.04400000000000003	0.002029943060856597
0.045	0.00381344992736355	0.04500000000000003	0.002053279572448814
0.046	0.0016590397232885	0.046000000000000034	0.0023215843013097114
0.047	0.000484246256357906	0.047000000000000035	0.002102456118194295
0.048	0.00343759835073887	0.048000000000000036	0.002323837771856356
0.049	0.00164786770663547	0.04900000000000004	0.002123966996353259
0.05	0.00108579497495939	0.05000000000000004	0.002062616551103155
0.051	0.000157986600989313	0.05100000000000004	0.002090312701358042
0.052	8.5520974977449e-05	0.05200000000000004	0.0020983784171220675
0.053	0.000268689777456528	0.05300000000000004	0.002035508776978997
0.054	0.000498097162430973	0.05400000000000004	0.0020465077905546486
0.055	0.000626668619116381	0.05500000000000004	0.002021845989010823
0.056	0.000561338657417891	0.05600000000000004	0.002010386032973018
0.057	0.00060672864439956	0.057000000000000044	0.001997964714508905
0.058	0.000804195777136424	0.058000000000000045	0.001939645351057385
0.059	0.000935391677311765	0.059000000000000045	0.0019913066578446698
0.06	0.000906731335083967	0.060000000000000046	0.001705620036432254
0.061	0.00100863637703223	0.06100000000000005	0.0017412714657283983
0.062	0.00127872753085312	0.06200000000000005	0.0014954089393778328
0.063	0.00113648722819597	0.06300000000000004	0.0016173194225164128
0.064	0.000980083239973235	0.06400000000000004	0.0014351496809680993
0.065	0.00143387296496799	0.06500000000000004	0.00139146400465654
0.066	0.00136119382587076	0.06600000000000004	0.0014390872456603251
0.067	0.00119921132883301	0.06700000000000005	0.001325611958368433
0.068	0.00205806591488281	0.06800000000000005	0.0013577886586618355
0.069	0.00120737195804755	0.06900000000000005	0.001213636231928196
0.07	0.00117311522214611	0.07000000000000005	0.0012337589580073195
0.071	0.00096872755031082	0.07100000000000005	0.0012440926084586594
0.0720000000000001	0.000768693377175181	0.07200000000000005	0.0011355385172401602
0.0730000000000001	0.00104343252834755	0.07300000000000005	0.0010658965669871532
0.0740000000000001	0.000915304811448944	0.07400000000000005	0.0010821834877223755
0.0750000000000001	0.000918835695671717	0.07500000000000005	0.001033275472020043
0.0760000000000001	0.000986690953010839	0.07600000000000005	0.0010533098207843367
0.0770000000000001	0.00156106226288364	0.07700000000000005	0.0010971275462186457

0.0780000000000001	0.00182232432304279	0.0780000000000006	0.001021452708415366
0.0790000000000001	0.000948303131951011	0.0790000000000006	0.0010431463240004857
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0.0870000000000001	-0.000215516627841786	0.0870000000000006	8.659881781432654E-4
0.0880000000000001	-5.74415755312477e-05	0.0880000000000006	7.823932919107441E-4
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0.107	- 0.000228977226408604	0.10700000000000008	5.893549836043663E-4
0.108	- 0.000889412565050083	0.10800000000000008	5.88694719914767E-4
0.109	-0.00031508053544079	0.10900000000000008	5.330229620101741E-4
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0.118	0.0004271670905061	0.11800000000000009	4.965959873382405E-4
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0.156	-0.0112930492805712	0.1560000000000001	2.569837600510969E-4
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0.16	-0.003550028884237	0.16000000000000011	2.659916818947526E-4
0.161	-0.0047771858732335	0.16100000000000012	2.6842792100589027E-4
0.162	-0.00760338155554671	0.16200000000000012	2.6525984102840464E-4
0.163	-0.00442986003763322	0.16300000000000012	2.2621480833732316E-4
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0.166	0.000289793030311047	0.16600000000000012	2.7104753869206834E-4
0.167	0.000560598086643386	0.16700000000000012	2.7211381816804367E-4
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0.17	0.00126495091841083	0.17000000000000012	1.9802484146993045E-4
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0.175	-0.00317545539705085	0.17500000000000013	2.3503260004986763E-4
0.176	-0.00193164415425523	0.17600000000000013	1.9362651632027258E-4
0.177	-0.00207703433409437	0.17700000000000013	2.0316360312532108E-4
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0.206	-0.000770469610590314	0.20600000000000016	1.2703640974021866E-4
0.207	-0.000851257308666779	0.20700000000000016	1.2451118230969967E-4
0.208	-0.000437828710856677	0.20800000000000016	1.2420259429711425E-4
0.209	-0.000733798730211629	0.20900000000000016	1.524849149463145E-4
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0.215	-4.82817835617991e-05	0.21500000000000016	1.5988643486989143E-4
0.216	0.000205004896940661	0.21600000000000016	1.3781067412467918E-4
0.217	-7.40100057920534e-05	0.21700000000000016	1.6071893584294168E-4

0.218	-0.000341505733861782	0.21800000000000017	1.4216080025497688E-4
0.219	-0.000300725693093305	0.21900000000000017	1.407989141432944E-4
0.22	2.72783766310987e-05	0.22000000000000017	1.4198964609924303E-4
0.221	-0.000237275748072315	0.22100000000000017	2.0027542144852249E-4
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