BITS PILANI K.K. BIRLA GOA CAMPUS

Department of Mechanical Engineering

THERMAL COMFORT IN AIRCRAFT

ME F461

REGRIGERATION AND AIR CONDITIONING (RAC)

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1 INTRODUCTION:

Passengers thermal Comfort is one of the prominent cabin-related issues. The influential parameters affecting thermal comfort are **air temperature, air velocity, relative humidity, and black globe temperature.** The aircraft cabin is densely populated and narrow, so we have to consider these factors mainly for longer duration flights.
The average air temperature lies between 21-24 ºC, still in most of flights besides temperature regulation, the thermal discomfort is felt appreciably. Therefore many methods are continuous being investigated and researched for getting better ECS.
So in this study, we have tried to study the ECS parameters like temperature, velocity, humidity and their effect on thermal comforts of passengers.

1.1 Thermal Comfort:

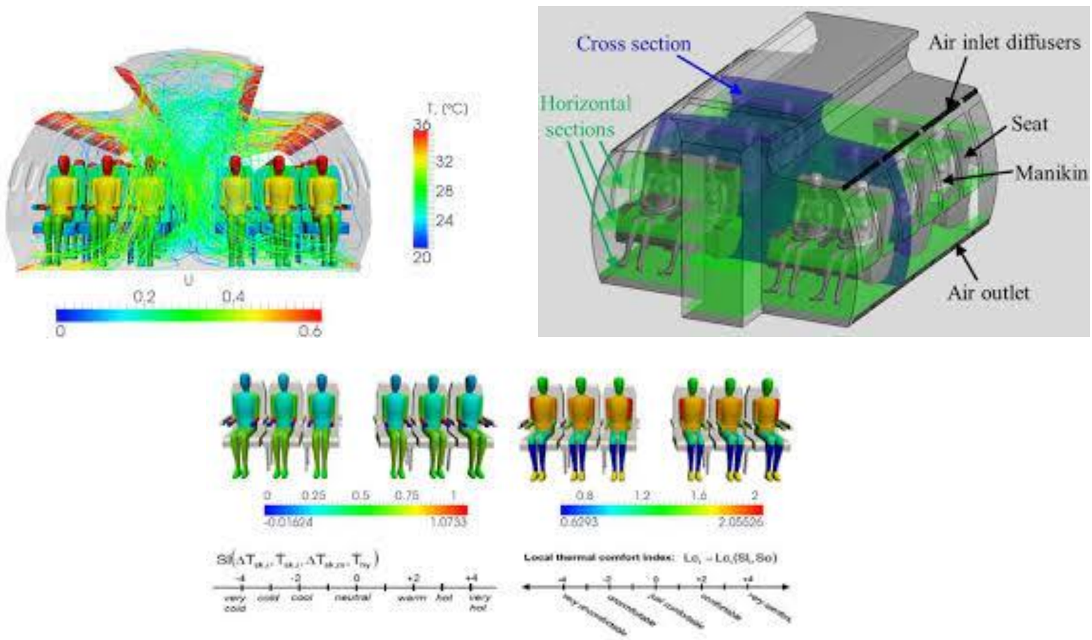

Figure 1.1 : Temperature and velocity Distribution

Thermal Comfort is that condition of mind which expresses the satisfaction with the thermal environment – absence of irritation or discomfort due to heat or cold. Thermal comfort is adaptive and it changes from season to season and from person to person. It is for a particular part of body or the entire body. ASHRAE 55 standards are used.
A humidity sensor, thermometer, globe thermometer, anemometer (measures air temp. and air speed) are general measuring instruments

- Ensuring thermal comfort means to maintain the inner body temperature between 36-38 ºC. This is achieved when heat produced by body is lost and no heat is stored or excess heat loss than produced doesn’t take place. There should be no unbalance between heat produced and heat lost.
- **Thermal comfort depends on 2 personal (activity and clothing) and 4**

environmental factors (Air Temperature, Relative Air Humidity, Relative Air Velocity, Mean Radiant Temperature)

- The human body produces mechanical work (W) along with heat (Q), and the total energy produced is called metabolic rate (M=W+Q). It is expressed in Met (1 Met = 58.1 W/m^2). Higher activity = Higher Metabolic rate :
  - Sitting – 1 Met.
  - Sleeping – 0.8 Met
  - sedentary activity – 1.2 Met
  - standing or light activity – 1.6 Met
  - medium activity – 2 Met
  - Driving – 1 to 2 Met
  - cooking – 2 Met
  - cleaning – 3 Met,
  - playing – 4 Met
  - Hiking – 6 to 7 Met
  - Running – 3 to 8 Met.
- Human body exchanges heat with the surrounding through
  - Convection: C (skin, air temperature and speed),
  - Radiation: R (skin and enclosing temperature), (The apparent size of each radiant surface should be taken into consideration along with temperature called the View factor.)
  - Transpiration: T (sweating and respiration–depends on relative humidity of air),
  - Conduction: H (thermal contact between body and solid object – Thermo physical characteristics and skin temperature)
    Q= C + R + E + H
- Clothing: Thermal Resistance - 1 clo = 0.155 m^2.K/W (summer = 0.5 clo, winter = 1 clo, naked person = 0 clo).
- Mean Radiant Temperature (T_{mrt}): It is the uniform temperature of an imaginary enclosure, in which the radiant heat transfer from the human body is equal to radiant heat transfer in the actual non-uniform enclosure. It is the function of the position at which it is measured. It changes with finish of the reflective surface.
- Air temperature has a direct impact on thermal comfort. Mean radiant temperature takes into the consideration the air velocity and temperature & globe temperature. The globe temperature is the temperature of air only, but it takes into account the effects due to radiation (Globe Thermometer). Optimal RH range : 40-60 %
- There are lines for air velocity in psychrometric chart. So we can calculate the DBT and WBT/ RH and use it in chart to find the air velocity.

1.2 Factors Affecting Human Thermal Comfort

The PMV is an index which predicts the average climate assessment value of a large group of people. The PPD Index provides a quantitative prediction of the number of people that will be dissatisfied with a certain ambient atmosphere.

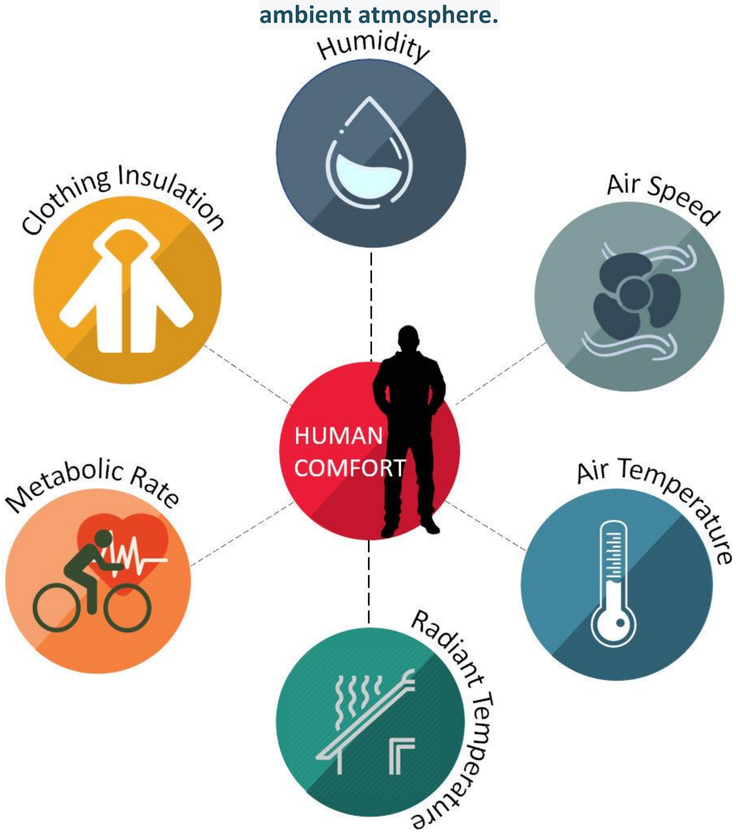

Figure 1.2 : Factors affecting PMV

1.2.1 Predicted Mean vote (PMV):

Both PMV and PPD model were developed by Povl Ole Fanger. It is an empirical fit to the human sensation of thermal comfort and predicts the average vote of a large group of people on the seven-point thermal sensation scale where:

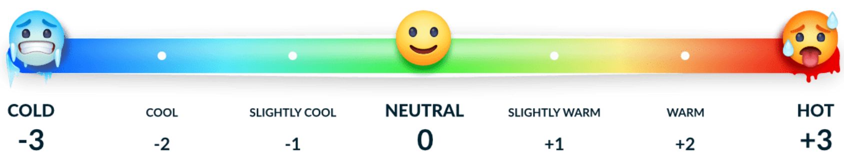

Figure 1.3 : PMV Scale

1.2.1.1 Empirical Formulation:

$$PMV = [0.303 \cdot exp(-0.036 \cdot M) + 0.028] \cdot \{ (M-W) - 3.05 \cdot 10^{(-8)} \cdot fcl \cdot [(Tcl + 273.15) - (Tr + 273.15)] - fcl \cdot hconv \cdot (Tcl - Ta) - 3.05 \cdot [5.733 - 0.007 \cdot (M-W) - 0.001 \cdot pw] - 0.42 \cdot [(M-W) - 58.15] - 0.0173 \cdot M \cdot (5.867 - 0.001 \cdot pw) - 0.0014 \cdot M \cdot (34-Ta)\}$$

M : Metabolic rate (W/m^2)
W : Effective Mechanical power (W/m^2)
fcl : Clothing surface area factor
Tcl : Clothing surface temperature (°C)
Ta : Air temperature (°C)
Tr : Mean radiant temperature (°C)
pw : Water vapour partial pressure (Pa)
hconv : Convective heat transfer coefficient ($W/(m^2.K)$)

*Tcl = 35.7 – 0.028 *(M-W) – Icl * { 3.96*10^(-8) * fcl*[(Tcl+273.15)^4 -(Tr-273.15)^4] + fcl*hconv*(Tcl-Ta) }*

hconv={ 2.38|Tcl-Ta|^0.25 for 2.38*|Tcl-Ta|^0.25>12.1*Var }*
*={ 12.1*Var for 2.38*|Tcl-Ta|^0.25<12.1*Var }*

*fcl = {1 + 1.290*Icl for Icl<=0.078 m2.K/W}*
*= {1.05 + 0.645*Icl for Icl>0.078 m2.K/W}*

Var : relative air velocity (m/s)
Icl : clothing insulation (m2.K/W)

1.2.2 Predicted Percentage of Dissatisfied (PPD):

Even after getting to know to the thermal sensation for a population, we also need to get the level of satisfaction of occupants in space. It establishes a quantitative prediction of the percentage of thermally dissatisfied occupants. The factors responsible for this discomfort are drafts, abnormally high vertical temperature differences between the ankles and head, and/or floor temperature.

*PPD = 100 – 0.95exp (-0.03353*PMV^ (4) – 0.2179*PMV^ (2))*

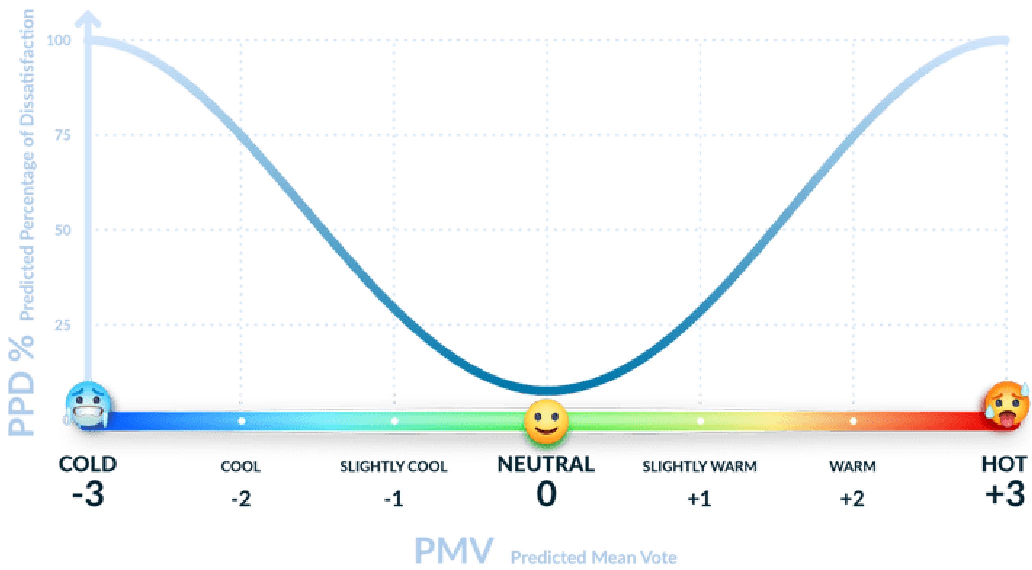

Figure 1.4 : PMV vs PPD

2 Objective:

To develop a numerical model for predicting thermal comfort inside an aircraft cabin using PMV/PPD model and to report the effects of various parameters on Thermal comfort.

3 Methodology:

- A literature survey was done to understand the Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) model by **Povl Ole Fanger (1970)** and the usage of these two parameters in determining the thermal sensation felt by human beings.
- Further available experimental data was sought on the thermal environment inside aircrafts. This study focuses on **short-haul domestic flights** and the experimental values were obtained from previous research publications.
- The PMV/PPD model requires both external and personal factors**. The temperature inside an aircraft cabin is assumed to be uniform and CFD model was created to obtain the velocity distribution.**
- A base model consisting **of one row of 6 seats (merged into two sets of seats)** in a **single aisle economy class configuration** for the base model ***Airbus A320*** was created using SolidWorks.
- **A Microsoft Excel spreadsheet with a user-defined function was used for obtaining the PMV and PPD values for an input of the air temperature, velocity, relative humidity, mean radiant temperature and clothing factor using the velocity distribution as an input from the CFD simulation. Further the excel spreadsheets were used to create a 5th degree regression polynomial of the variation of the PMV and PPD with the velocity (other parameters kept constant) and the polynomial was imported into the CFD post-processor to generate contours.**
- The CFD model was setup and ran in Ansys Fluent 2021 Student version package with the appropriate boundary conditions (described below) to obtain the velocity distribution.
- For the contours, the values for the PMV and PPD were obtained with respect to variation in air velocity with other parameters being kept constant (described in Results section). A fifth-degree polynomial regression curve was created of PMV and PPD with air velocity as the varying parameter and polynomial was used to create a user-defined variable in CFD post (post-processor**). Three contour planes were used, on the window seat, middle and aisle seat.**
- Further two lines, one in the head region and the other in the foot region each running parallel to the seat were created and the velocity magnitudes along these lines was **imported into excel and the average PMV and PPD values in the head and foot region a passenger seated in the window , middle and aisle seats was found**. The logic behind this was that this allowed the personal factors such as clothing and metabolic rate to be varied unlike the contours where they were fixed.

4 Modelling and simulation:

4.1 Geometry

The geometry was created based on the dimensions of a narrow body Airbus A320 base variant. A row of seats is created with one aisle. A 0.5 m section of the fuselage is modelled. Air inlet vents are provided on the top and the air exhaust vents are in the bottom near the seat. The inlet and outlet ducts are designed for the required flow rate with optimum inlet velocity.

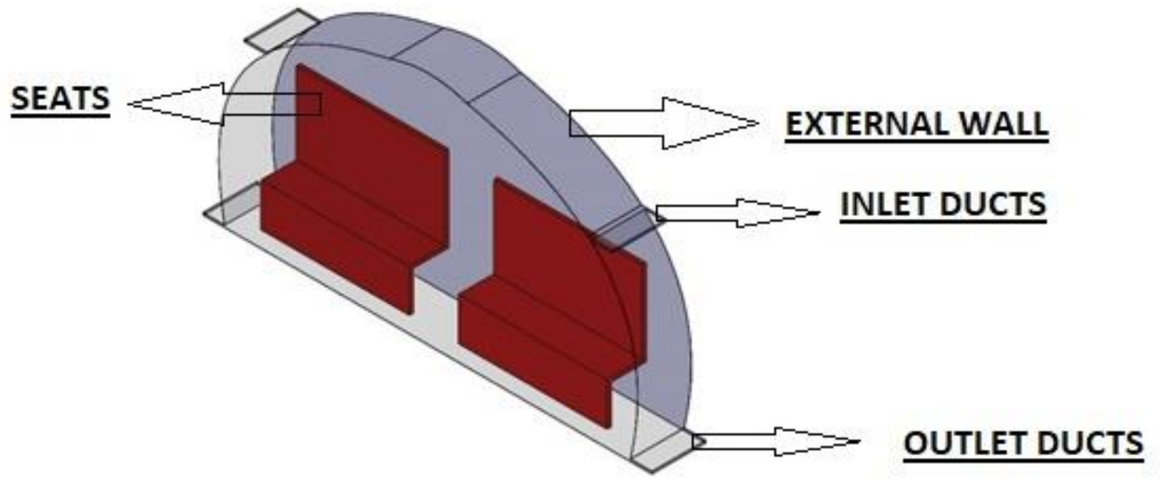

Figure 4.1(a) : Geometrical Design with Sections

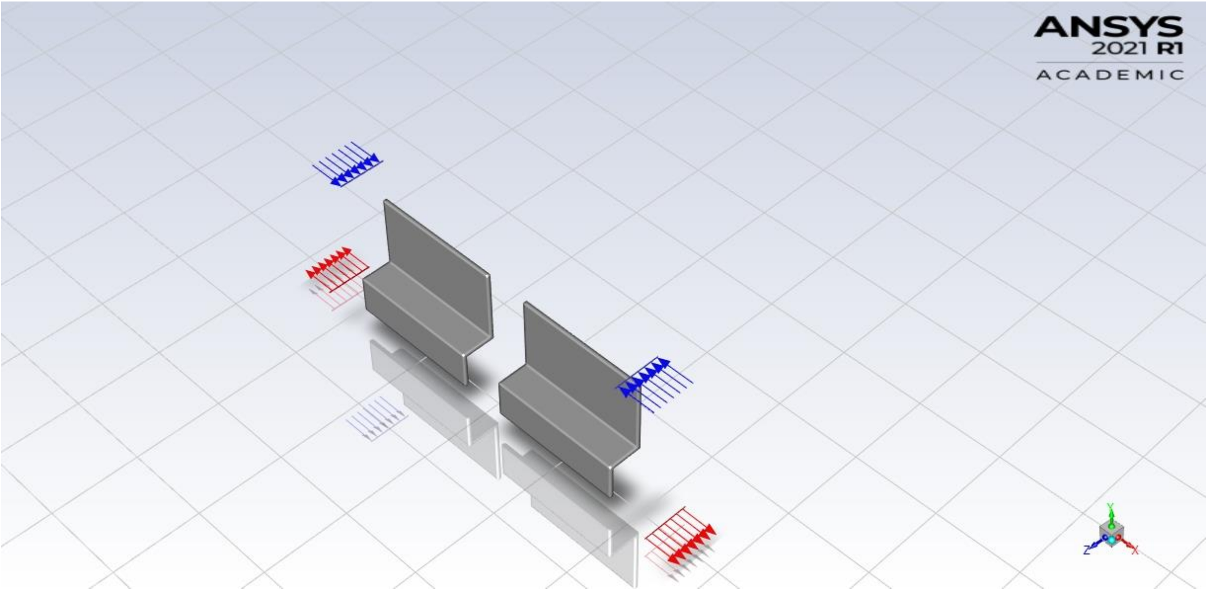

Figure 4.1(b) : Seats with inlet and outlet sections

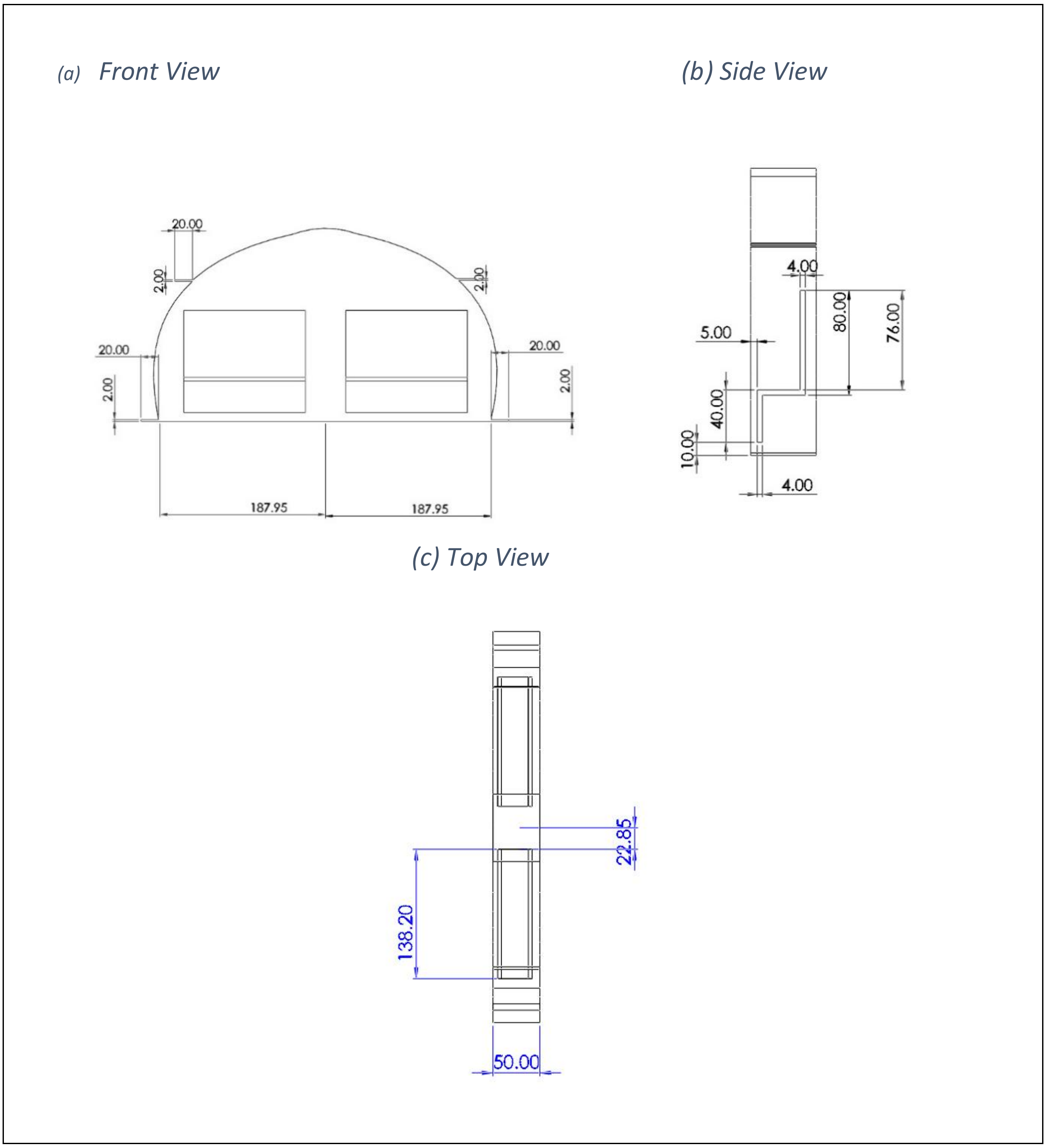

Figure 4.1(c) : Dimensions of the geometry. The model was created based on the Airbus A320 narrow body cabin. All dimensions are in centimeters

4.2 Mesh

Meshing was done using Ansys Student Mesher. An element size of 2.5 mm was set, and number of nodes created was 285075. As stated, before the geometry used was wet volume of the cabin space to simulate fluid flow. A minimum mesh quality above 0.8 was achieved for a large proportion of the cells.

Number of nodes	285075
Element size	2.5e-002 m
Min quality	0.52128
Maximum Quality	1
Average Quality	0.97677
Standard Deviation	4.4286e-002

Table 4.2 : Mesh Data

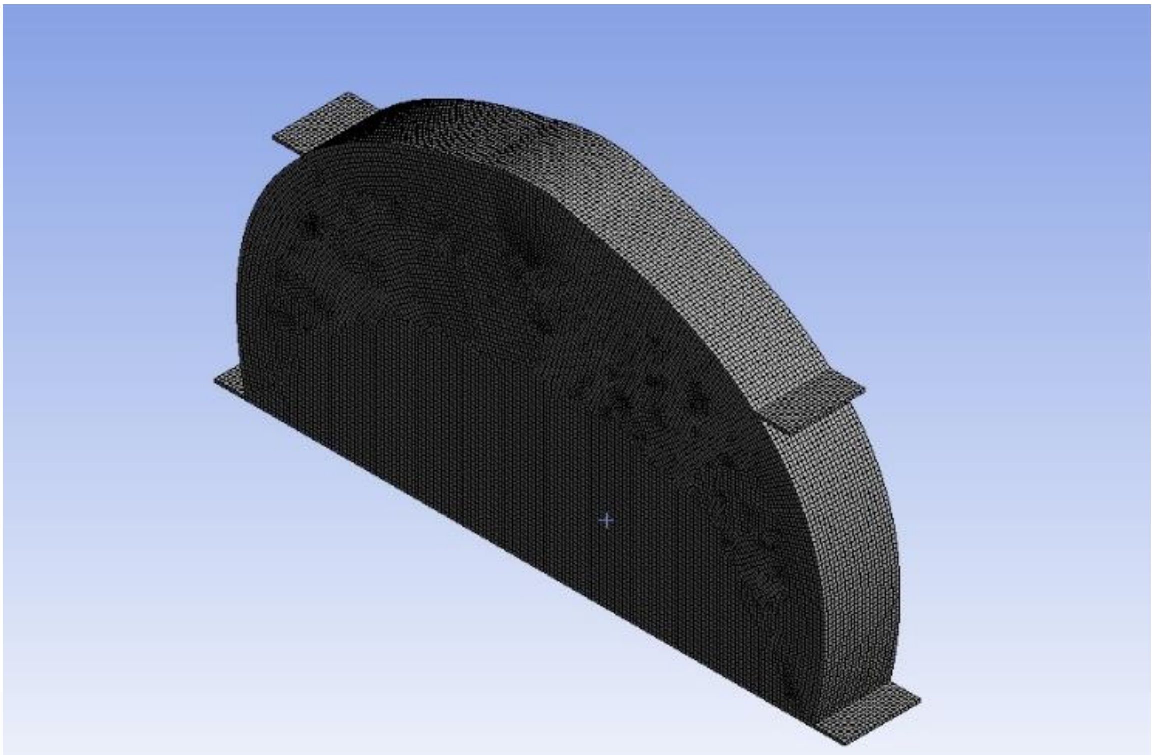

Figure 4.2 : Mesh

4.3 Case Setup

The cases considered in the study as based on experimental studies conducted. In the study 14 domestic flights with roughly 1 hour duration were considered, and indoor air quality based on temperature and relative humidity was investigated. The findings were also validated through questionnaires of passengers and cabin crew. The aircraft model used for the study was the Airbus A319, a short-range member of the A320 family. The experimental results relevant to the present computational study are summarized below:

Flight Duration (Hours: minutes)	Number of passengers and crew	Average Relative Humidity (%)
1:23	140	20.2
1:07	70	20.2
1:17	143	22.1
1:09	113	20.7
1:17	146	21.1
1:20	134	17.9
0:48	87	22.3
0:39	95	22.1
1:26	81	19.0
1:07	84	19.2
0:49	107	23.2
0:37	74	24.7
0:50	102	27.0
0:37	80	25.9

Table 4.3 : Experimental reference data for the study

Questionnaires filled by subjects reported a relative humidity between 10-40% and temperature in range of 21-25 degrees Celsius.
Based on the experimental data referenced to, a cabin temperature of 20, 22 and 25 degrees Celsius and 15, 20, 25, 30% relative humidity has been used in the present study.
Ansys Fluent Student 2021 version was used for the present study. The post processing was done CFD Post.
The Reynolds Averaged Navier Stokes (RANS) based turbulence model – **the k-epsilon model** was used for the present study. Standard wall functions were used.

4.4 Boundary Conditions

The inlet ducts on the top portion of the cabin is used to admit air at 20 degrees Celsius for refrigeration of the cabin. The Airbus A320 model used an ECS with an average flow rate of 2kg/s of air into the cabin. Since the fuselage length of the actual A320 is 37.5 meters but the model considered in the study is 50 cm, the flow rate for the reduced section is taken as 0.02667 kg/s and based on the inlet duct area, a velocity inlet of 2.1768m/s with absolute reference frame and 5% turbulence intensity was given.
The seats are approximated as the human passengers on the flight. The heat generation due to metabolic activity of human being is taken as 70 W/square-meter. The thermal conditions given for the seats are therefore convection type with heat transfer coefficient (W/square-m K) and thickness of 0.002 meters, characteristics of human body. The heat generation due to metabolic activity was given as *Heat Generation Rate* (36.96 W/meter-cube) calculated based on the surface area and volume of a seat. A new material of human body was created with density 1000 kg/cube-m, specific heat of 3600 J/(KgK) and thermal conductivity of 0.21 W/ (m K).
The external walls are considered *Adiabatic,* and both the seats and the external walls are given *no-slip* condition for fluid flow.
The front and back portions of the geometry are given *symmetry* boundary condition.

5 Post processing methodology

5.1 Contours

Four sets of contours are presented with the relative humidity values as 15, 20, 25, 30% and the air temperature as 20 degrees Celsius. For each case three sets of planes are used.The planes used for creating the contours are positioned for the three seats included in one row, the aisle seat, middle seat, and the window seat, this was done to obtain a full picture of the thermal comfort conditions in the cabin.

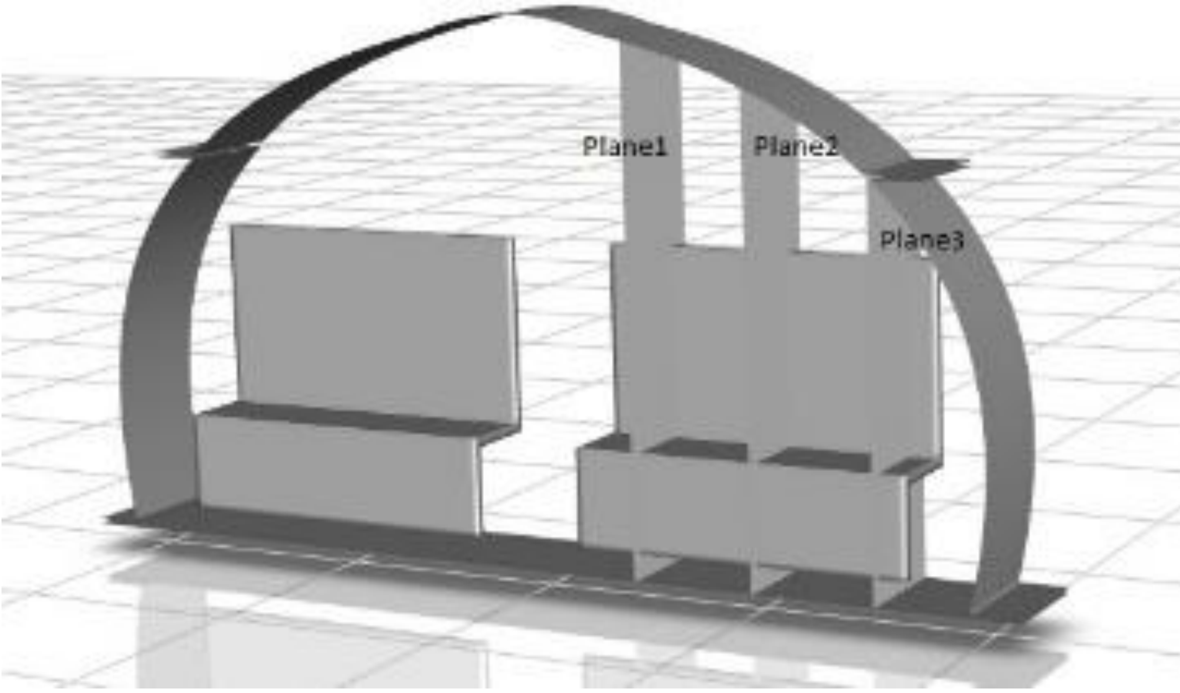

Figure 5.1 : Planes used for contours: Plane 1- Aisle Seat, Plane 2- Middle Seat, Plane 3- Window Seat

The assumptions used in creating the contours are:

- Human Metabolic energy production rate is taken as 70 W/square-m.
- Rate of mechanical work is taken as 0, since passengers are stationary and do not have any large movements inside the flight.
- Mean Radiant Temperature and inside cabin temperature is taken as 20 degrees Celsius.
- Relative humidity is taken as 15%, 20%, 25% and 30%.
- The basic clothing insulation is taken as *clo*=1 (0.155 W/square-mK), a fully clothed person.

A spreadsheet of values of PMV and PPD for air velocity values between 0 to 2m/s was created with an increment of 0.01 m/s for each value of relative humidity. **Linear regression** was used to create a 5th degree best fit polynomials for both PMV and PPD with a**ir velocity as the variable** was created for the four sets of values obtained for each of the relative humidity used in the study. The polynomial was used to create a User-Defined Variable in CFD-Post and the contours were obtained for each of the four cases. The regression was created using MS Excel.

The link to the spreadsheet drive folder is given below, the title of the spreadsheet is *"Thermal_comfort_model."*In the spreadsheet, six parameters need to be inputted:

- Altitude felt by passengers.
- Metabolic rate in W/m2
- Clothing level
- Air Relative humidity
- Air temperature in Degrees Celsius

The spreadsheet then automatically calculated the PMV and PDD values for the range of velocity and plots two graphs of PMV and PPD and the regression polynomial.

[Link to spreadsheet]:https://drive.google.com/drive/folders/1nuKaHl10tS9TpcRQmBt-eE0T5m9cXD-B?usp=sharing

5.2 Line Velocity Data

The velocity magnitudes of the flow inside the aircraft cabin were obtained along two lines, one running along the passenger's head, and the second below in the foot area. Each of the lines was split into three for the window, middle and aisle seats as shown in the figure [4]. **A separate simulation of the air-flow inside the cabin without the thermal conditions was used just to obtain the velocity distribution.**

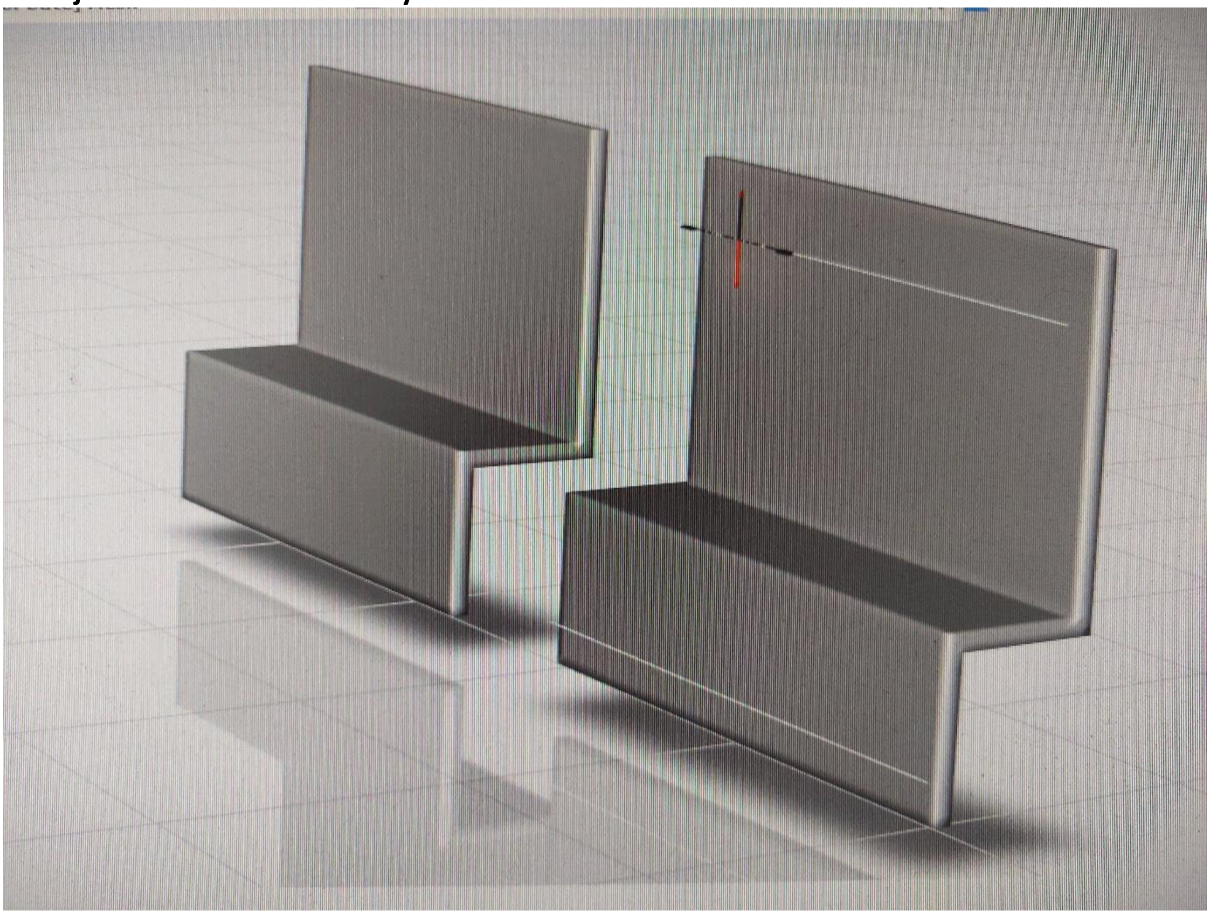

Figure 5.2 : The top and bottom white lines are the lines considered for the head and foot areas.

The velocity values along these lines were obtained and imported into three spreadsheets –

1. Window_seat.xls

2. Middle_seat.xls
3. Aisle_seat.xls

Each of the spreadsheets has the velocity magnitude along the lines of head and foot imported into them. **For this study the Middle Seat is focused upon. The Middle_Seat.xlxs has a sheet with the title “Final_Calculation” wherein the input values (highlighted in yellow) are the clothing factor of the passenger, altitude and metabolic rate. The spreadsheet the automatically displays the average PMV and average PPD in the table provided for the temperature and relative humidity ranges.**
[Link to spreadsheet]:https://drive.google.com/drive/folders/1nuKaHl10tS9TpcRQmBt-eE0T5m9cXD-B?usp=sharing

[Note: For the spreadsheets to work, the Macros need to be enabled]

6 Results:

6.1 Velocity Distribution

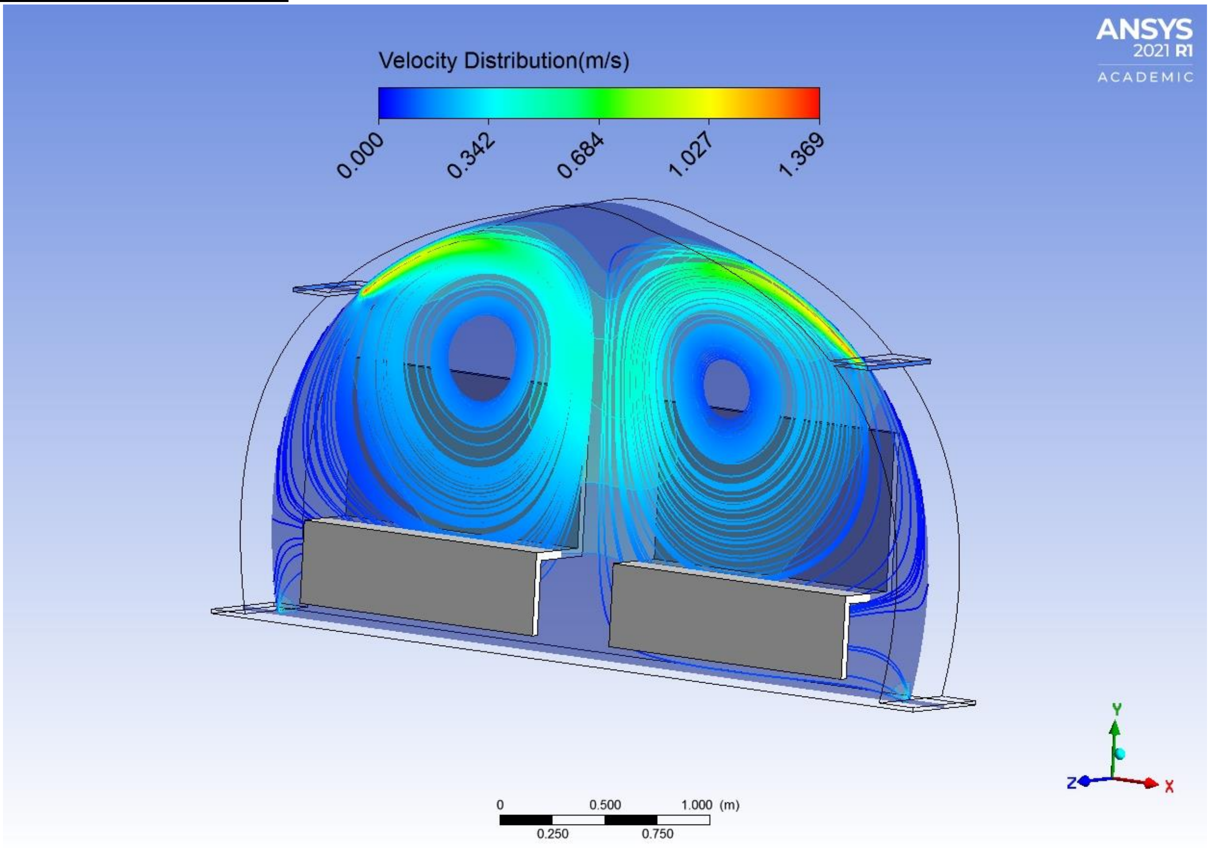

Figure 6.1 : Velocity Magnitude in cabin

6.2 Contour results:

All the contours were created with the altitude set to ground level(0) and clothing factor as ‘1’ and metabolic rate as 70W/m2 and cabin temperature as 20 degrees Celsius.

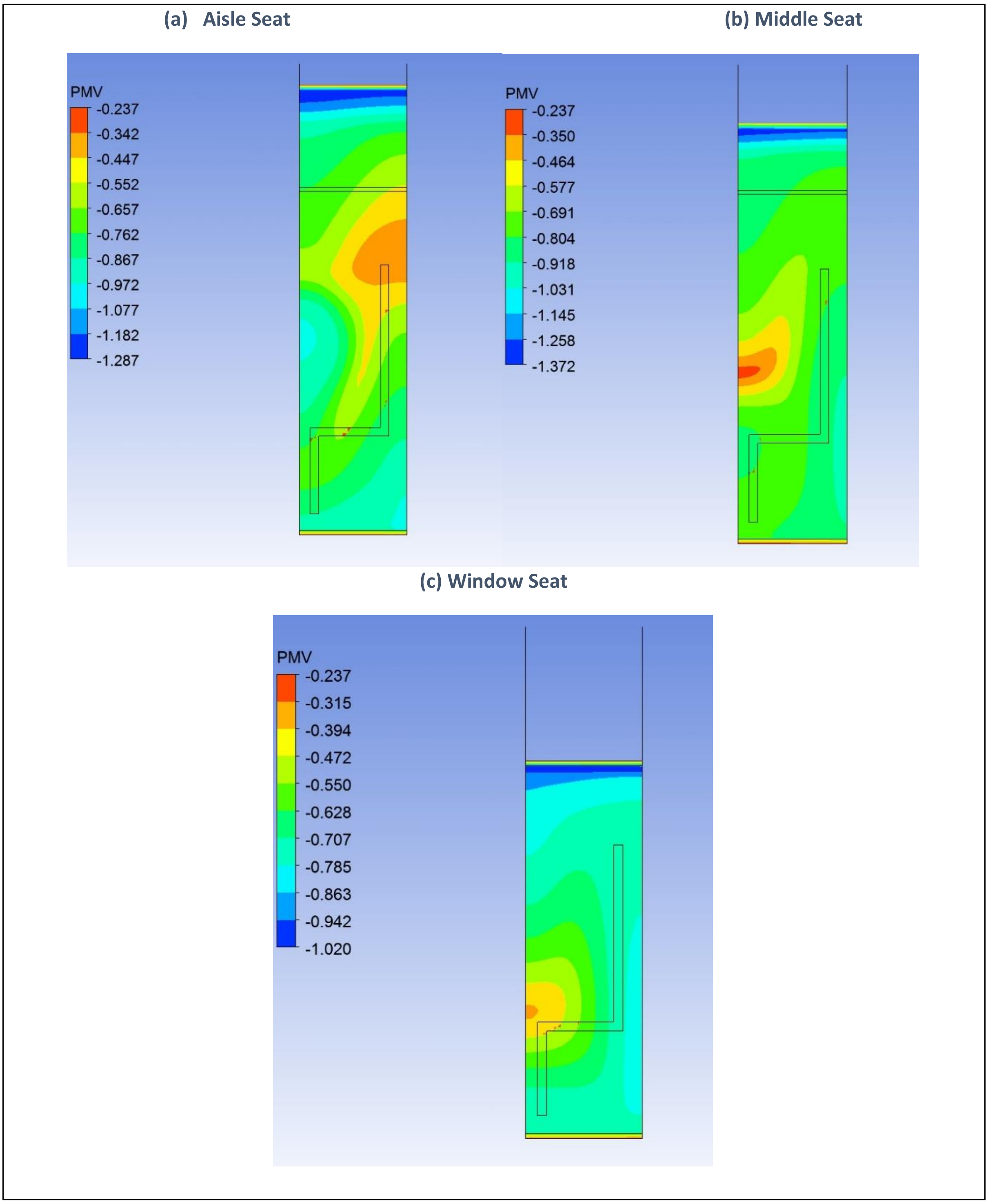

Figure 6.2(a) : Predicted Mean Vote for Relative Humidity 15%

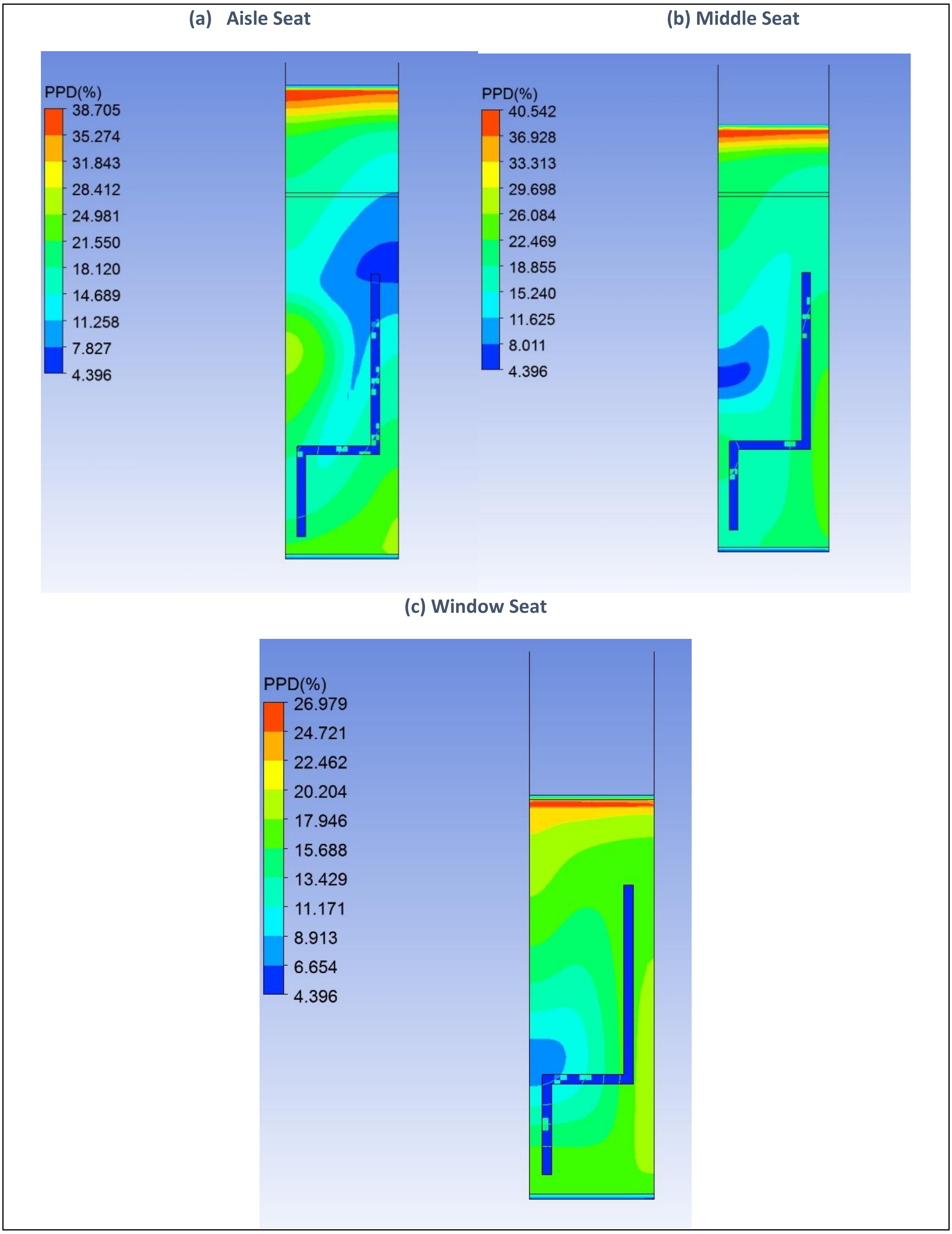

Figure 6.2(b) : Predicted Percentage of Dissatisfied for Relative Humidity 15%

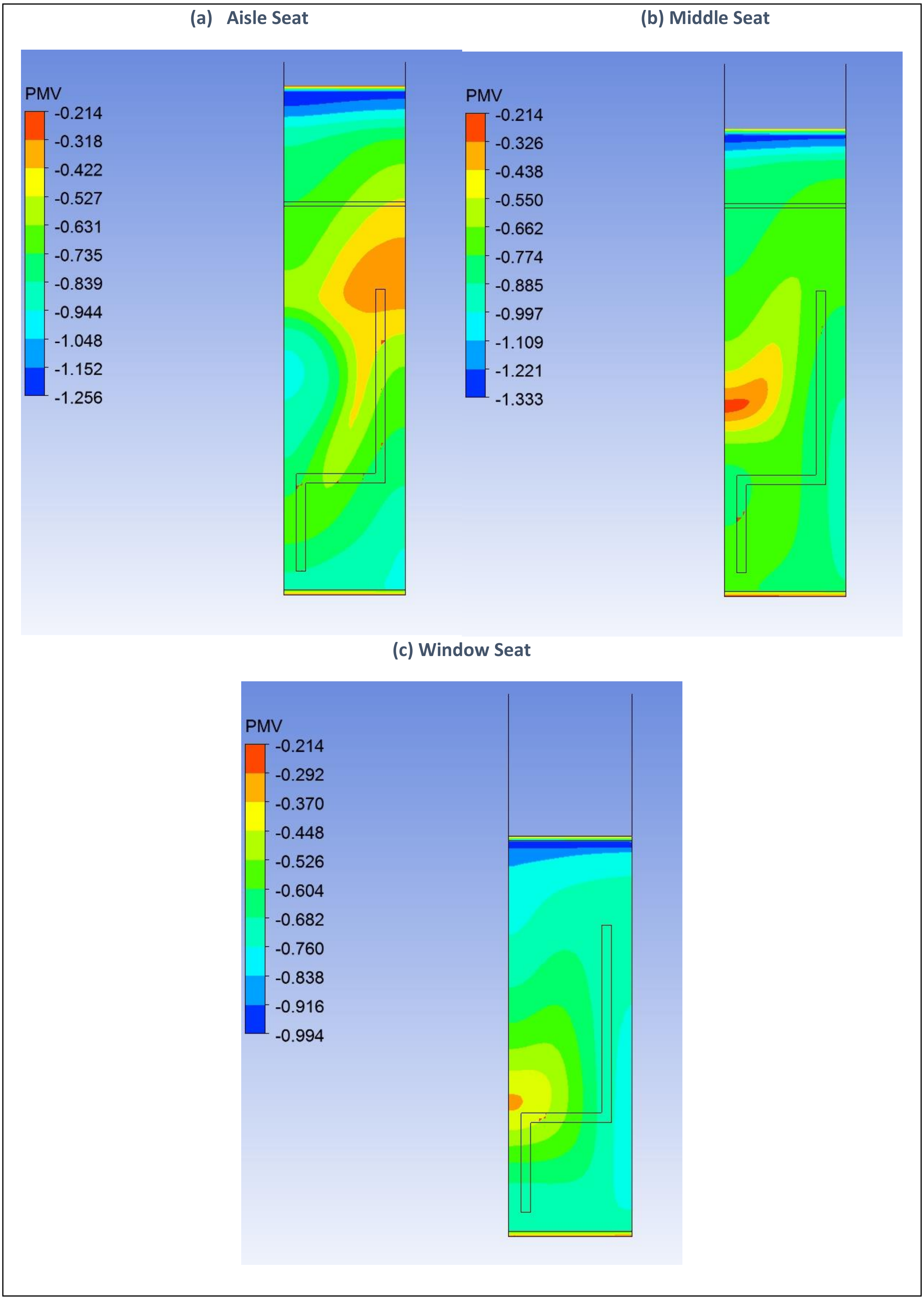

Figure 6.2(c) : Predicted Mean Vote for Relative Humidity 20%

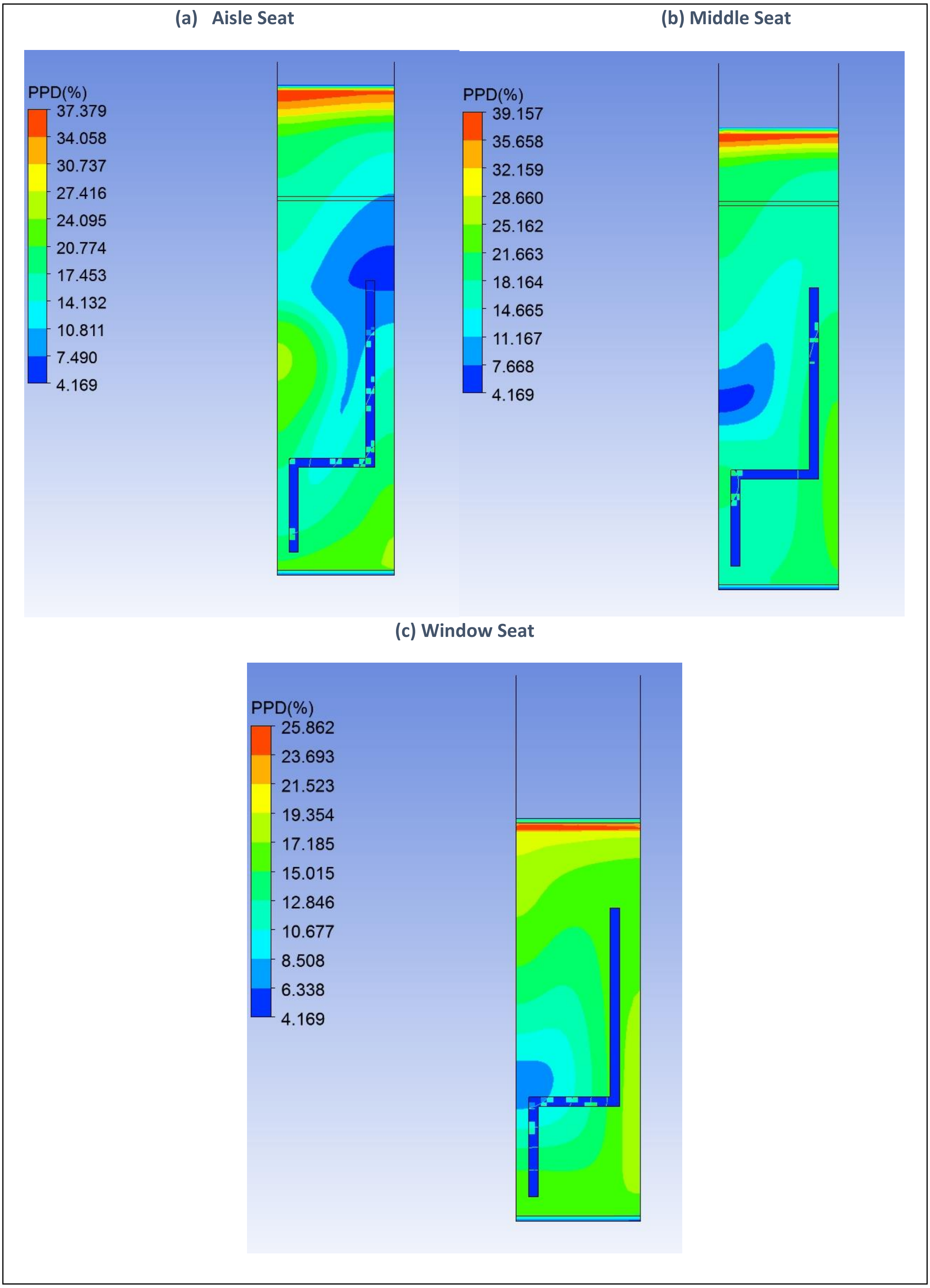

Figure 6.2(d) : Predicted Percentage Dissatisfied for Relative Humidity 20%

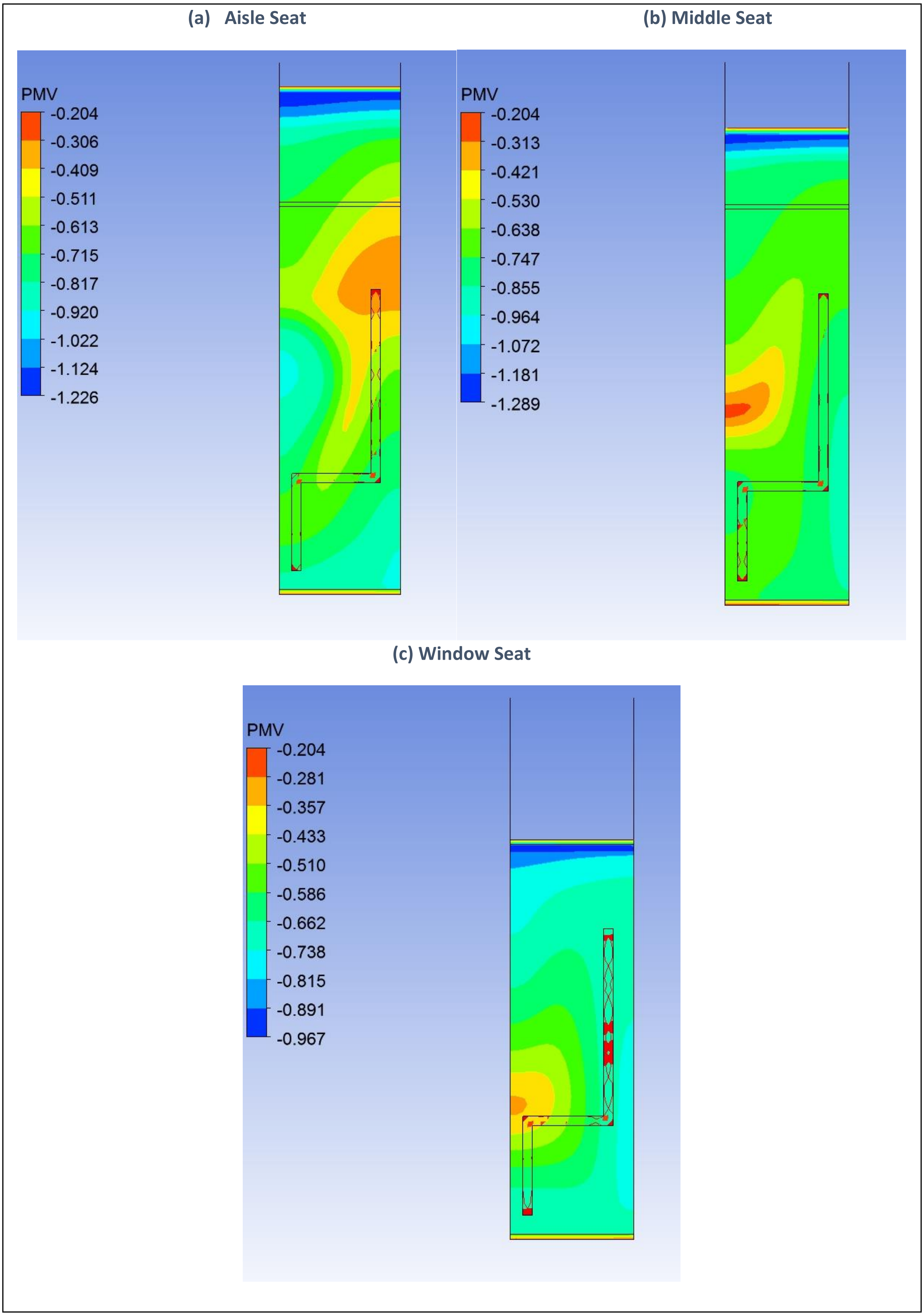

Figure 6.2(e) : Predicted Mean Vote for Relative Humidity 25%

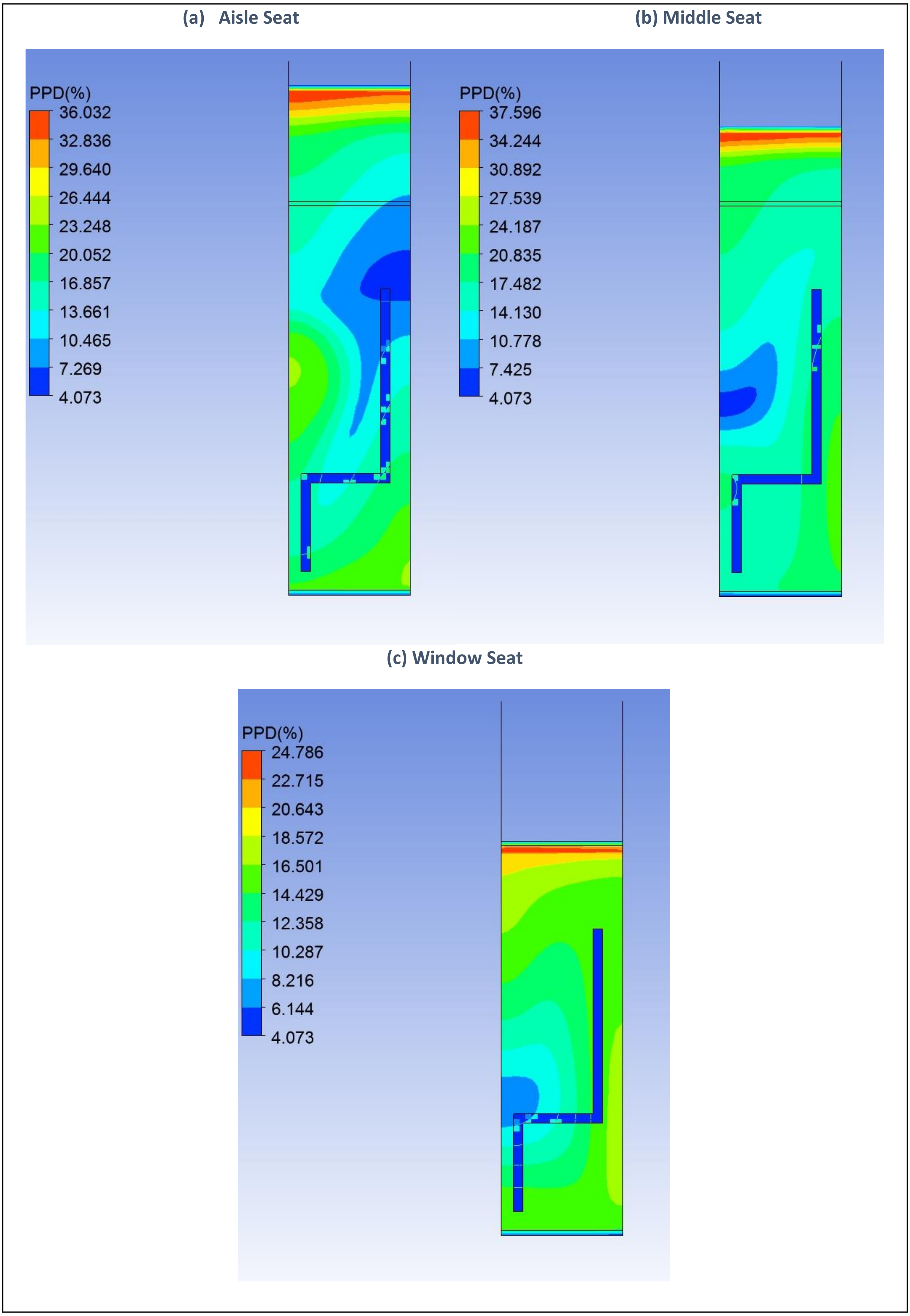

Figure 6.2(f) : Predicted Percentage Dissatisfied for Relative Humidity 25%

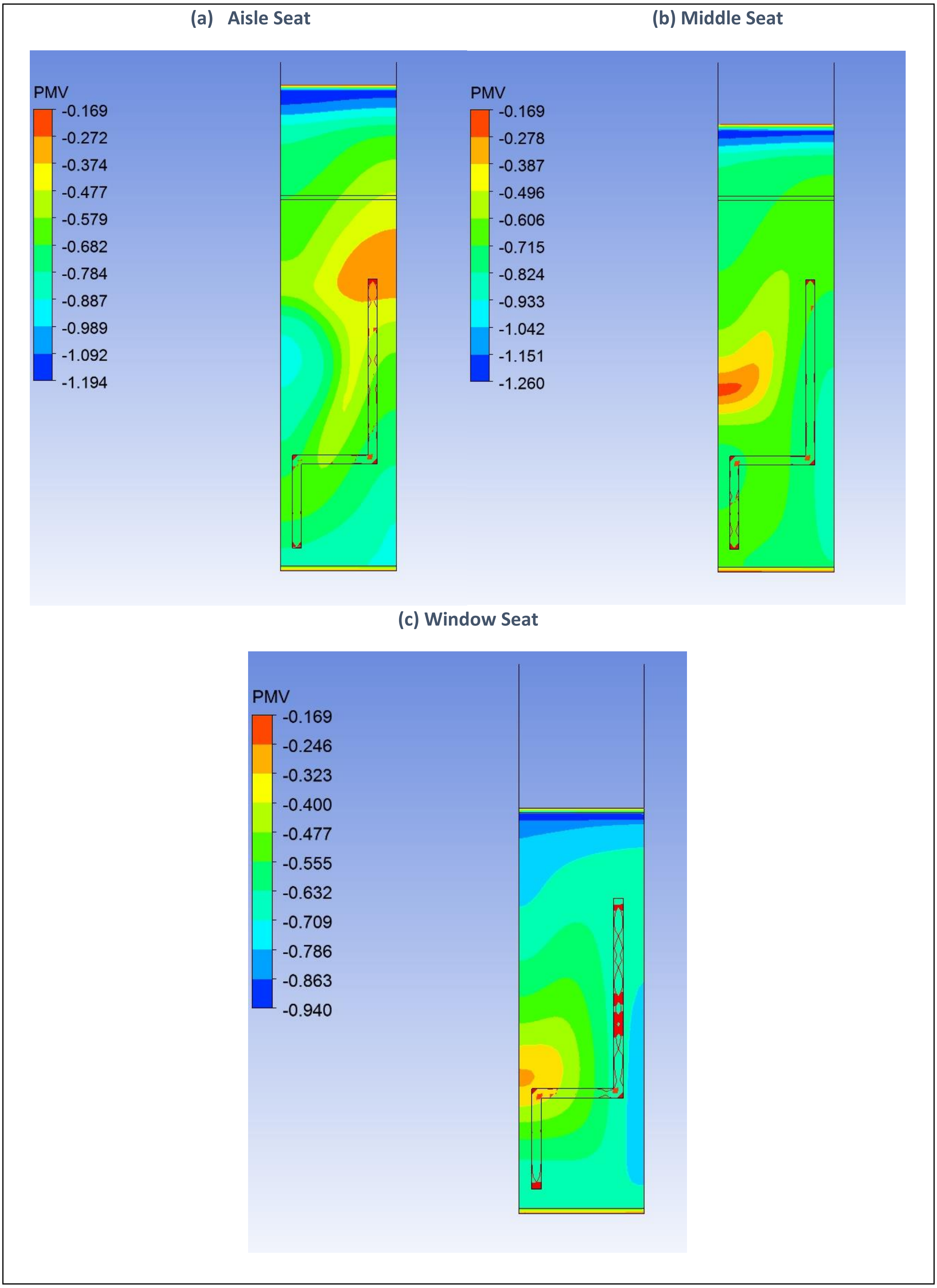

Figure 6.2(g) : Predicted Mean Vote for Relative Humidity 30%

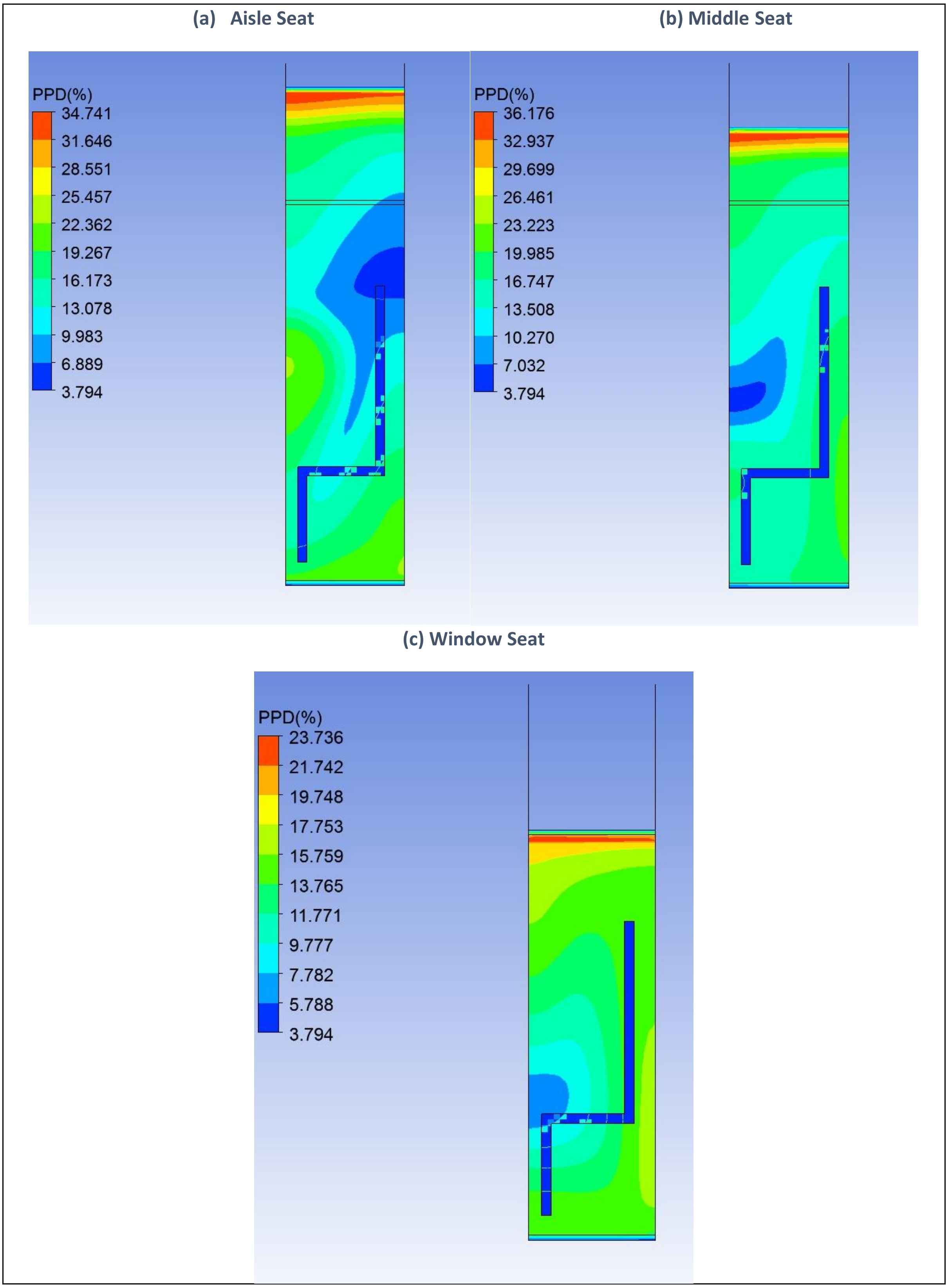

Figure 6.2(h) : Predicted Percentage Dissatisfied for Relative Humidity 30%

6.3 Line Velocity Results

These results were obtained from the excel spreadsheet and has been taken for the middle seat position. At a particular value of Cabin temperature and Relative humidity the average values of PMV and PPD are presented. **These results are used for drawing conclusions since they are able capture more of the passenger area than the contours can and variation in cabin temperature , Altitude (5000 ft for cruise level as felt by the passengers) , and personal factors can be obtained which was not possible in the contours.**

Relative Humidity (%)	15		20		25		30	
Cabin Mean Air Temperature	PMV	PPD	PMV	PPD	PMV	PPD	PMV	PPD
20	-1.225	36.623	-1.197	35.260	-1.169	33.915	-1.141	32.591
22	-0.705	15.667	-0.674	14.742	-0.642	13.858	-0.610	13.015
25	0.072	5.240	0.110	5.383	0.148	5.587	0.186	5.852

Clothing level 0.7, Metabolic Rate 70W/m2 at Ground Level at Head

Relative Humidity (%)	15		20		25		30	
Cabin Mean Air Temperature	PMV	PPD	PMV	PPD	PMV	PPD	PMV	PPD
20	-1.414	46.330	-1.386	44.856	-1.358	43.389	-1.330	41.933
22	-0.894	22.081	-0.863	20.906	-0.831	19.768	-0.799	18.669
25	-0.117	5.419	-0.079	5.264	-0.041	5.169	-0.003	5.134

Clothing level 0.7, Metabolic Rate 70W/m2 at Cruise Level at Head

Relative Humidity (%)	15		20		25		30	
Cabin Mean Air Temperature	PMV	PPD	PMV	PPD	PMV	PPD	PMV	PPD
20	-0.637	13.655	-0.609	12.918	-0.581	12.213	-0.553	11.540
22	-0.206	5.984	-0.174	5.734	-0.143	5.526	-0.111	5.358
25	0.440	9.098	0.478	9.830	0.516	10.627	0.554	11.490

Clothing level 1, Metabolic Rate 70W/m2 at Ground Level at Head

Relative Humidity (%)	15		20		25		30	
Cabin Mean Air Temperature	PMV	PPD	PMV	PPD	PMV	PPD	PMV	PPD
20	-0.826	19.530	-0.798	18.567	-0.770	17.635	-0.742	16.733
22	-0.395	8.358	-0.363	7.856	-0.332	7.395	-0.300	6.975
25	0.251	6.366	0.289	6.793	0.327	7.282	0.365	7.834

Clothing level 1, Metabolic Rate 70W/m2 at Cruise Level at Head

Table 6.3 : Line velocity Results

7 Discussion, Limitations and Future

1. The four tables represent the passenger comfort in the middle seat of the cabin. The ideal conditions for the aircraft cabin can therefore be adjusted based on the metabolic rate and clothing level of each passenger.
   - **For a passenger with clothing factor as 0.7, the higher temperature of 25 degrees Celsius is referable for comfort.**
   - **The effect of the temperature appears to be higher at cruise altitude.**
   - **A higher relative humidity is recommended at cruise level and a lower value at ground level for the temperature of 25 degrees.**
   - **For a heavily clothed person (as most passengers are in commercial flights) a cabin temperature of 22 degrees gives more comfort, and a higher value of relative humidity at 30 is most comfortable at both cruise and ground level.**
2. The amount of conclusions and inferences that can be derived from the computational model is immense; since the variables that go into defining the thermal comfort of the passengers are higher and each of them present new possibilities and results upon which aircraft manufactures and airlines can design their cabin layouts. **The purpose of this study was to develop a robust computational methodology which can be used by aircraft engineers to design aircrafts for the future.**
3. Limitations however exist in the present study; the most important is that cabin temperature has been assumed to be uniform everywhere which is not always the case**. Very little temperature variation was observed in the CFD model results, which indicates that further refinement is required to accurately capture the thermal environment inside the aircraft cabin.**
4. The cabin model itself is only considering one row of seats, and the seats themselves have been approximated as humans. A more accurate model can be developed if the authors are able to get access to research versions of computational software.
5. The present model can be expanded further to include a full scaled model of an aircraft, refined mesh, higher number of line segments and contours to accurately capture velocity distribution within the cabin. Further the geometric model can be modified to include the windows as a source of solar radiant heat during day time flying.
6. The range of temperature and relative humidity can also be considered limited since it is based on only one experimental study conducted in one small region of the world. Most experimental data can be referred to further expand the model. Other factors such as number of passengers and seasonal conditions which have and indirect effect on thermal comfort can also be incorporated into the excel spreadsheets.

8 References:

Online Resources:

1.PMV-PPD (lth.se)

2. Tools and Additional Material (colorado.edu)

Drive link to referred papers:

https://drive.google.com/drive/folders/1KF0mjSf9p-ndjgp1ppchImRwxlrYxO7f?usp=sharing