

# VEPZO – Velocity Propagating Zonal Model for the prediction of air-flow pattern and temperature distribution in enclosed spaces

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## Abstract

This paper presents the VEPZO-model (VELOCITY Propagating ZONal model), the first three dimensional airflow model for indoor spaces that has been implemented in Modelica. The model predicts airflow and temperature distribution in a room. The main feature of the VEPZO model is that each zone has a characteristic velocity depending on entering and leaving airflows. This characteristic velocity is propagated into space ensuring the propagation of driving airflows. The VEPZO model can be interfaced to other models of the Modelica Standard library. In an application example a displacement ventilation in a twin-aisle aircraft cabin is investigated. The temperature in the occupied zones is predicted between 20.6 and 23.0 °C.

*Keywords: zonal model, airflow modeling, Modelica*

## 1 Introduction

Accurate energetic modeling of buildings and vehicles requires the consideration of included air. In a multizone model the air in a room or zone is considered perfectly mixed. Air exchanges occur between rooms or with the environment. This approach is implemented in the “Buildings” library [1]. If a higher level of detail is needed, the zonal model is an alternative that can be implemented in Modelica. A zonal model divides a room into typically 10 to 100 zones exchanging air through flow paths. At the last Modelica conference Bonvini and Leva [2] presented an implementation of a two-dimensional zonal model. In parallel to their work another Modelica-based zonal model, VEPZO (Velocity Propagating Zonal Model) has been built at the Fraunhofer-Institute for Building Physics. Former zonal models have some drawbacks that make them unsuitable for the use in Modelica. The airflow is supposed to rest in the zones and to move in the flow models. Once air enters a zone, its velocity is dissipated. Therefore, the

zonal formulation is not valid in areas with driving flows due to jets or plumes [3]. Here, Inard et al. [4] suggest using jet-, plume- or thermal boundary layer correlations to compute the amount of air entrained from the surrounding “normal” zones. A Modelica implementation of this suggestion would require the model to change its set of equations during runtime to be able to switch from the zonal model to a correlation model where needed. However, this feature is currently not provided by Modelica. Furthermore, the flow models are based on the Bernoulli-equation resulting in a square root function of the pressure difference. At zero pressure difference, the square root is numerically unstable due to its infinite gradient. Therefore, the following modifications have been made in the VEPZO model:

- Calculation of the acceleration or deceleration of the airflow between two adjacent zones with a viscous loss model
- Introduction of the length of an airflow path into the zonal equations
- Use of the airflow velocity as a property in the zones

Bonvini and Leva [2] use a similar approach, however the VEPZO model differs from their implementation in the following points:

- Use of Modelica.Media-models for air properties computation
- Use of stream-connectors
- A flow model connects to two zones only and not to adjacent flow models
- Three dimensions implemented
- Viscosity is a parameter with value 0.001

## 2 Implementation of the VEPZO model

The two main components of the VEPZO model are a zone model and a flow model (Figure 2). The zone

(cube) and the flow (grey rectangle) models are connected by ports (rhombs) to form a room. These ports allow the exchange of relevant information between the flow and the zone model:

```

replaceable package Medium = Modelica.Media.Air.SimpleAir
Modelica.SIunits.Pressure p;
Records.Position position;
Records.Velocities velocities;
flow Modelica.SIunits.MassFlowRate mdot;
stream Modelica.SIunits.SpecificEnthalpy h;
stream Modelica.SIunits.Density d;
stream Modelica.SIunits.MassFraction Xi[Medium.nXi];
stream Real ExtraProperty[Medium.nC];
Real dv_perp[2];
Real sum_d2v_perp_weighted;
    
```

Figure 1: Implementation of connector, position and velocities contain coordinates and characteristic velocity of zone,  $dv\_perp$  is the gradient of characteristic velocity perpendicular to flow direction,  $sum\_d2v\_perp\_weighted$  is a quantity used for viscosity computation

The flow models have two ports to connect adjacent zones. Each zone has six ports, one for each boundary. A Boolean parameter is assigned to each port to make the distinction whether the port is connected to a flow model or whether it is adjacent to a room boundary surface. Furthermore, each zone has a heat port (red square) allowing heat exchanges with models of other components like e.g. heat sources or walls. Air properties are computed from Modelica.Media. Depending on the application, the air model can be changed from dry to moist air. Even pollutants could be taken into account.

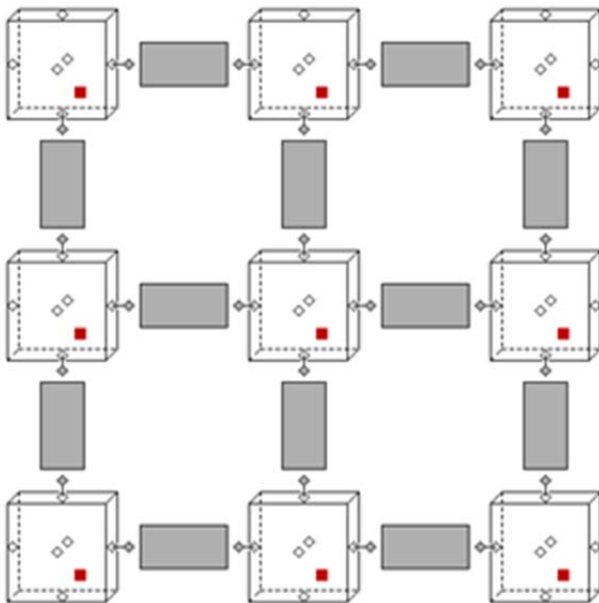


Figure 2: VEPZO model in x-z direction (y not shown); cubes: zones; grey rectangles: flows; rhombs: airflow ports; red solid squares: heat ports.

The main task of the zone model is to compute the mass and enthalpy balance and air properties (density, enthalpy, pressure, temperature, etc) using air models of Modelica.Media. Furthermore it determines a characteristic velocity and viscous losses. The main task of the flow model is to compute the airflow rate between two adjacent zones. Furthermore, the flow models are used to calculate the velocity gradient needed for the calculation of viscous losses. The governing equations will be more precisely described in the following sections.

## 2.1 Zone model

The mass and energy conservation are implemented in the VEPZO model in the same way as in former zonal models. Air contained in a zone  $i$  of volume  $V_i$  with density  $\rho_i$  and specific enthalpy  $h_i$  is assumed to be perfectly mixed. In the zones, the dynamic conservation of mass (Equation ( 1 )) and enthalpy (Equation ( 2 )) are implemented. The mass conservation takes into account the amount of air  $m_{i,j}$  exchanged with adjacent zones and airflows provided by various sources or sinks  $m_{source,i}$  (ventilation, openings, etc.) in zone  $i$ . When steady state is reached the sum of all exchanged airflows in a zone becomes zero. Mass flows are defined as flow variable and enthalpies as streams. This ensures the proper sign attribution to flows an enthalpy selection depending on flow direction. Heat flows  $Q$  due to convection to walls or heat sources contained in the zone are added to the thermal energy balance.

$$\frac{\partial \rho_i}{\partial t} = \frac{\sum_j \dot{m}_{i,j} + \sum_{sources} \dot{m}_{source,i}}{V_i} \quad (1)$$

$$V_i \cdot \rho_i \cdot \frac{\partial h_i}{\partial t} = \sum_j \dot{m}_{i,j} \cdot h_{i/j} + \sum_{sources} \dot{m}_{source} \cdot h_{i/source} + \sum_{heat\ flows} \dot{Q} \quad (2)$$

A new feature of the VEPZO model is that a characteristic velocity vector  $(u,v,w)$  is assigned to the zones. Knowing the mass flow and its direction across each of the zone's surfaces, the flow velocity across these surfaces is determined:  $u_{left}$ ,  $u_{right}$ ,  $v_{front}$ ,  $v_{back}$ ,  $w_{bottom}$ ,  $w_{top}$  for the left, right, front, back, bottom and top surfaces. If a zone is adjacent to a wall, the mass flow and velocity across the corresponding

surface are considered to be zero. For each Cartesian direction the flow pattern is checked. If air flows through the zone, the entering velocity is assigned to the characteristic velocity component. If air enters from both sides, the difference of the velocities is assigned. If air leaves on both sides, zero is assigned (shown for x-direction in Figure 3 and Table 1)). Iterating this procedure for all Cartesian directions yields the characteristic velocity of a zone.

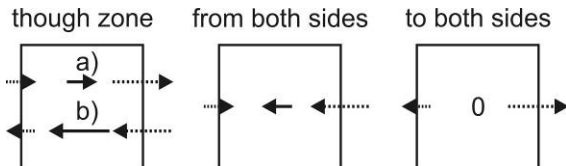


Figure 3: Assignment of characteristic velocity to a zone, dotted arrows: airflow across zone boundaries, solid arrow: characteristic velocity of zone. Left: flow through the zone, case a) left to right, case b) right to left, Middle: Air enters zone from both sides, Right: Air leaves zone on both sides

Table 1: Assignment of characteristic velocity components of a zone

Flow through zone	Characteristic velocity
left → right	$u_{left}$
right → left	$u_{right}$
left and right → zone	$u_{left} - u_{right}$
zone → left and right	0

The zone shares the information about its characteristic velocity with the flow models surrounding it. This enables the VEPZO model to propagate the air-flow velocity throughout the room without needing special correlations like jets or plumes.

## 2.2 Flow model

Two adjacent zones are connected by a flow model computing the exchange of air between them. The VEPZO model uses flow models in x-, y- and z-directions. The assumption of the VEPZO model is that air only flows along these specific directions. A new feature of the flow model used in the VEPZO model is that the length of a flow path is taken into account.

The air densities  $\rho$  considered in the flow models are the average densities of the air contained in the adjacent zones. The use of the actualStream-notation for

the density showed to result in longer simulation times. Furthermore, density differences in indoor applications are not considered important enough to introduce a major error to the simulation when averaging.

### 2.2.1 Geometrical properties of the flow model

Figure 4 shows the definition of zones and flows in the z-direction. Two zones  $i, j$  of height  $\Delta z_i, \Delta z_j$  and equal ground area  $A = \Delta x \cdot \Delta y$  are connected by the flow model “Flow\_ij”. The flow model is of area  $A$  and height  $\Delta z_{ij}$ . This height is equal to the distance between centres of zone  $i$  and  $j$ . The definition of flow models in the x- and y-direction is analogous.

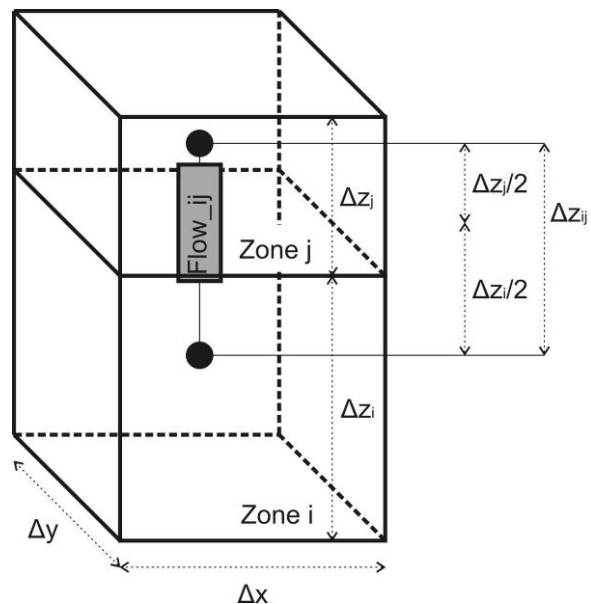


Figure 4: Definition of zones and flows in z-direction.

### 2.2.2 Forces acting on flow path

The flow model computes the airflow acceleration or deceleration from the forces acting on it. These forces are briefly described.

#### Pressure difference

Air contained in each zone has a certain pressure. When two zones of common surface  $A$  are connected by a flow model they process their pressure information  $p_i$  and  $p_j$ . The flow model calculates the resulting force  $F_p$  (Equation ( 3 )).

$$F_p = -A \cdot (p_j - p_i) \tag{ 3 }$$

### Momentum difference

The characteristic velocity vectors of adjacent zones are processed to the flow model. According to the flow direction (x, y or z) the flow model chooses the proper component of the velocity vectors ( $u_i, v_i, w_i$  and  $u_j, v_j, w_j$ ) to compute the force  $F_M$  resulting from the momentum difference between the adjacent zones (Equation (4) for x-direction).

$$F_{M,x} = -\rho \cdot A \cdot (u_j^2 - u_i^2) \quad (4)$$

### Gravitational forces

Gravitational force  $F_G$  only occurs in the z-direction. For the x- and y-direction, this force is zero. To compute the gravitational force, the area and length of the flow path are considered according to Figure 4.

$$F_G = -\rho \cdot g \cdot A \cdot \Delta z_{ij} \quad (5)$$

### Viscous forces

The viscous forces act parallel to the flow direction. In the selected approach of the VEPZO model, flows are connected and exchange information with zones only. However, to calculate the shear stress, an information exchange between parallel flow models would be necessary. To avoid connections between the flow models, viscous losses are calculated in the zone models but used in the flow models.

The characteristic velocity vector provided by zones enables the flow model to calculate the gradient of the two velocity components perpendicular to the flow model direction. For example, a flow model in z-direction can deliver the variation of the characteristic velocities  $u_i, u_j$  and  $v_i, v_j$  along the height  $\Delta z_{ij}$  (Figure 5). If a wall is adjacent to the zone, the velocity at the wall is assumed to be zero. Therefore, the gradient is equal to the characteristic velocity divided by half the distance of the zone's centre from the wall. Equation (6) provides an overview of gradient calculations in x-direction.

Gradient in flow model		Gradients at walls	
$\frac{\Delta v_{ij}}{\Delta x_{ij}}$	$\frac{\Delta w_{ij}}{\Delta x_{ij}}$	$\frac{2 \cdot v_i}{\Delta x_i}$	$\frac{2 \cdot w_i}{\Delta x_i}$

$$(6)$$

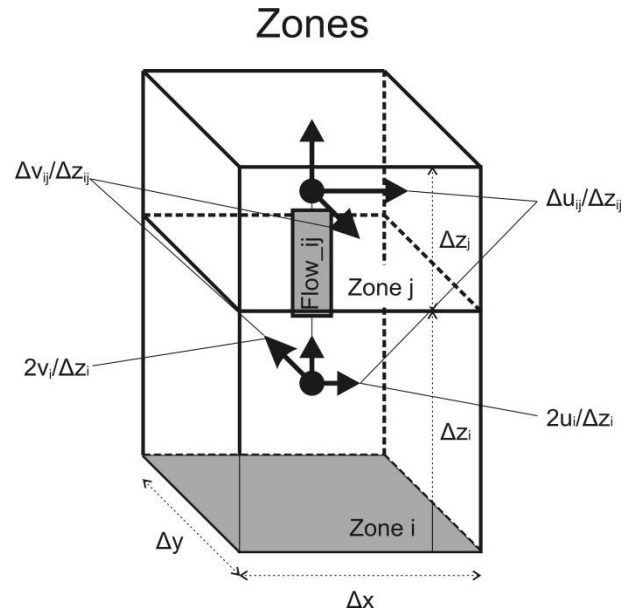


Figure 5: Computation of velocity gradient if lower wall of zone i is a wall

The gradient information is transmitted from the flow model to the zone model. In the zone model this gradient causes shear stresses on its boundaries. Summing these shear stresses along the boundaries yields the viscous forces  $F_{V,x}$ ,  $F_{V,y}$ , and  $F_{V,z}$  in the zones ( $\mu$ : dynamic viscosity of air):

$$F_{Vx,Zone} = \mu \cdot \left\{ \left[ \left( \frac{\Delta u}{\Delta y} \right)_{back} - \left( \frac{\Delta u}{\Delta y} \right)_{front} \right] \cdot \Delta x \cdot \Delta z + \left[ \left( \frac{\Delta u}{\Delta z} \right)_{up} - \left( \frac{\Delta u}{\Delta z} \right)_{down} \right] \cdot \Delta x \cdot \Delta y \right\} \quad (7)$$

Because the flow model covers half of the length of each adjacent zone (Figure 4) the resulting viscous force in the flow model is the sum of half of the viscous forces in the zones.

$$F_{Vx,Flow} = \frac{1}{2} \cdot (F_{Vx,Zone,i} + F_{Vx,Zone,j}) \quad (8)$$

### 2.2.3 Computation of airflow between zones with viscous loss model

The forces acting on a flow path are summed up. This yields the acceleration of the portion of air contained in the flow path connecting two zones.

$$A \cdot \Delta x_{ij} \cdot \rho \cdot \frac{du}{dt} = F_p + F_{M,x} + F_{Vx,Flow} \quad (9)$$

By this procedure, the distance between two zones and the area of the flow path are introduced into the model. The total loss along a flow path therefore becomes independent from the number of zones. Furthermore, no square root function is needed and numerical problems due to an infinite derivative do not occur.

The mass flow is obtained straightforward from the velocity in a flow path. This mass flow information is then transmitted to the zone model.

$$\dot{m}_x = \rho \cdot A \cdot u \quad (10)$$

#### 2.2.4 Modifications for non-cubic boundary zones

The idea of zonal modelling is to decompose a space into rectangular elements. However, if the modelled space is non-rectangular, non-cubic zone elements might be needed at boundaries. For this, a zone type similar to the standard zone type described in the previous sections is introduced where the sizes of each of the six boundaries surfaces, the zone's volume, its centre of gravity and its characteristic lengths can be entered manually to better match the actual geometry. For other geometries such as triangles, not needed sides of the element are attributed a very small size slightly above zero.

#### 2.2.5 Estimation of model coefficients

In the viscous loss model, the viscosity is used as a parameter to tune the model. Similar to the idea of using a turbulent viscosity to take into account losses, an apparent viscosity is used instead of the dynamic viscosity. During implementation of the VEPZO model,  $\mu = 0.001 \text{ Pa}\cdot\text{s}$  produced results that are in good accordance at steady state with case studies presented in previous publications [5-7]. Transient results have not been validated yet.

### 3 Investigation of a novel aircraft cabin ventilation

In this application example of the VEPZO model a novel ventilation system for an aircraft cabin will be investigated.

In current cabin designs air is supplied by ceiling inlets and extracted by slots in the dado-area on the left and right side of the cabin (Figure 6). This ventilation design leads to mixing ventilation.

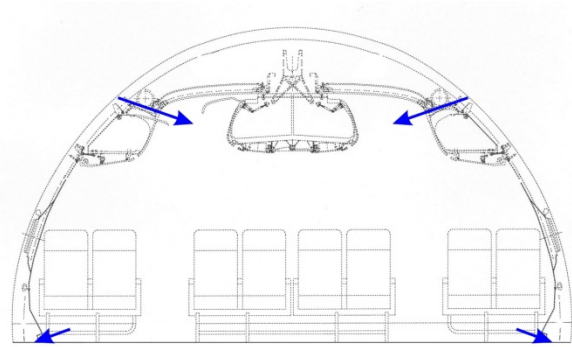


Figure 6: Cabin mixing ventilation air supply and extraction

In this paper a displacement ventilation is investigated where air is supplied by the aisle (60%), dado (20%) and side (20%) inlets. The total airflow rate is  $0.5 \text{ kg/s}$ .

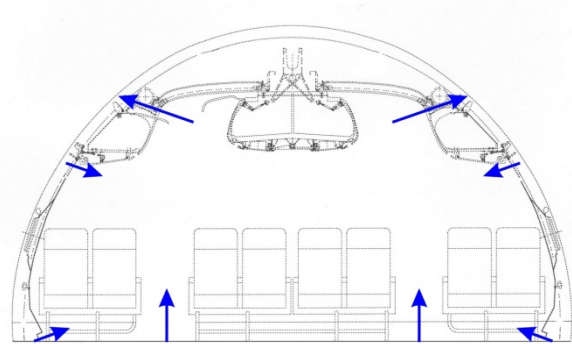


Figure 7: Cabin displacement ventilation air supply and extraction

#### 3.1.1 Aircraft cabin ventilation – Model

The implemented aircraft cabin model is derived from the Airbus A310 mock-up placed in the Fraunhofer Flight Test Facility [8] and represents a  $9.3 \text{ m}$  long and  $5.3 \text{ m}$  wide cross-section of the fuselage including the crown area, stowage bins, cabin, left and right triangle areas, cargo compartment and bilge (Figure 8). The air volume of the cabin is modelled by the VEPZO model, the air volumes of other compartments are modelled by a thermal capacitor with the appropriate thermal mass.

The cabin is subdivided into  $5 \times 3$  zones in the lower, occupied zone and into one zone for the upper part. In depth, the cabin is divided into three zones. The air supplies at the side, aisle and dado openings are modelled as mass flow sources. The ceiling outlet is modelled as a fixed pressure of  $750 \text{ hPa}$  corresponding to cabin pressure at flight altitude. The tempera-

ture of supplied air flows is controlled by the temperature in the adjacent zones (side and dado) or the average temperature in the occupied zone (aisle) (Table 2).

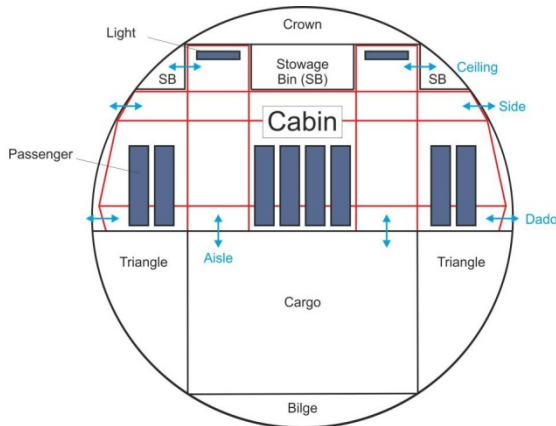


Figure 8: Fuselage section: blue arrows: inlets/outlets, red lines: zone limits in VEPZO model, black lines: walls

Table 2: Temperature setpoints and control locations

Inlet	Contol by	Setpoint
Side	Adjacent zone	22 °C
Dado	Adjacent zone	21 °C
Aisle	Average in occupied zone	22 °C

Walls are modelled by a succession of heat capacitances and heat resistances from the Modelica.Thermal library. Three materials (Table 3) are used in five wall layouts (Table 4) to model fuselage enclosures. Walls in the cabin are further decomposed into facets according to the size of the adjacent zones. These facets exchange convective heat with the air volumes. For the radiation model, surface temperatures of the facets of one wall are averaged. Radiation is calculated between these averaged wall surfaces using a radiation model suggested by Wetter et al. [9]. In other compartments, walls are not further decomposed into facets but exchange convective heat with the air node and radiative heat with other walls in the compartment.

Further admitted parameters (heat source intensities, convective heat transfer coefficients, long wave emissivity of surfaces, outside air temperature) are shown in Table 5.

Table 3: Material Parameters

Material	Density (kg/m <sup>3</sup> )	Specific Heat Capacity (J/kg·K)	Thermal Conductivity (W/m·K)
Aluminium	2700	835	235
Lining	1000	1500	0.16
Polyimide	1.2	1006	0.04

Table 4: Wall models

Name	Layers	Used for
Aluminium	Aluminium: 3 mm	Outside Wall Bilge Cabin Floor Cargo Floor
Thin Lining	Lining: 3 mm	Stowage bin
Thick Lining	Lining: 10 mm	Walls Car-go/Triangle
Cabin Outside Wall	Aluminium: 3 mm Polyimide: 80 mm Lining: 5 mm	Outside Walls Cabin
Other Outside Wall	Aluminium: 3 mm Polyimide: 80 mm	Outside Walls Crown and Triangle

Table 5: Heat flow related parameters

Parameter	Value
Convective Heat Transfer Coefficient	5 W/m <sup>2</sup> ·K
Long Wave Emissivity of surfaces	0,95
Outside Air Temperature	-27 C
Heat dissipation by passengers	
...by radiation	72 x 37,5 W
...by convection	72 x 37,5 W
(...total)	(5400 W)
Heat dissipation by lights	
...by radiation	1000 W
...by convection	1000 W
(...total)	(2000 W)

### 3.1.2 Aircraft Cabin Ventilation – Results

The simulation takes 31.9 s to converge on an Intel® Core™ i5 CPU @ 2.35 GHz 2.98 GB Ram computer. The simulation time is set to 10000 s as steady-state is achieved by then. “Radau IIa – order 5 stiff” is used to solve the equations. Figure 9 shows the

resulting supply and exhaust temperatures, temperatures in the zones and in the other compartments.

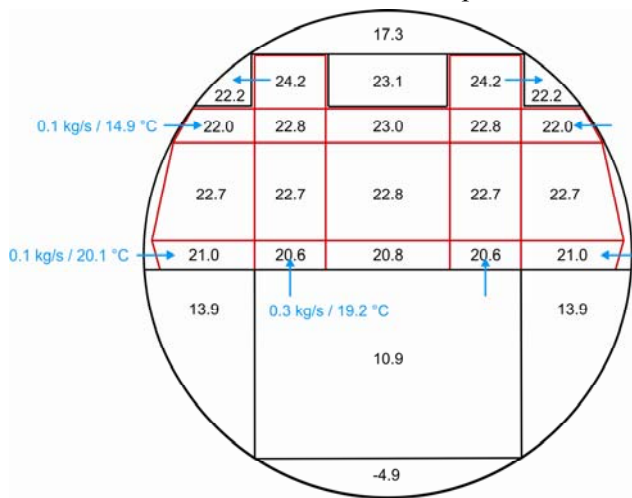


Figure 9: Results for cabin displacement ventilation system (Temperatures of zones in °C)

The warmest point in the occupied zone is just below the middle overhead bin. Here, air supply openings providing fresh air are relatively far away but heat production by passengers is relatively high. In spite of these adverse effects, the temperature is still in a comfortable range. Under the left and right overhead bins the lateral air supply avoids that the temperatures further raises compared to the zone below.

## 4 Conclusion

This paper presents the VEPZO model, a zonal model implemented in Modelica. The model makes use of and can be interfaced to models of the Modelica-Standard libraries. Compared to former zonal models, the VEPZO model is better suited for use in the Modelica environment.

In the shown application example the VEPZO model is used to estimate the impact of a displacement ventilation system in a two-aisle aircraft cabin. The simulation time is acceptable.

The use of Modelica to solve this problem showed to be advantageous as many of the auxiliary components (walls, air in other compartments, air properties in zones) are modeled with predefined models allowing the research engineer to concentrate on the core of the development, in this case the VEPZO model.

## 5 Acknowledgements

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