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Analysis of cooling loads and air circulation in the passenger compartment of the CR400AF fast train trailer car

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Abstract: The air conditioning system is a system that regulates air circulation and air temperature on the train. The temperature standard for fast train passengers is in accordance with Permen No. 7th year 2022 is 22°C - 26°C. To achieve this temperature, a cooling system is needed that is suitable for the cooling load. This research was conducted on the CR400AF fast train trailer car with the aim of knowing the factors that influence cooling loads, calculating and analyzing cooling loads which are used as a reference in determining air conditioning technical specifications, as well as analyzing air circulation that affects air humidity. The data analysis method used is the quantitative data analysis method. This method is carried out by collecting primary and secondary data to be used as a basis for calculations in answering the problem formulation. Data analysis was carried out by calculating the OTTV (Overall Thermal Transfer Value) according to SNI 03-6389-2000, calculating the cooling load using the CLTD (Cooling Load Temperature Difference) method according to SNI 03-6572-2001, and carrying out an air circulation test referring to Permen No. 7 of 2022. From the results of the analysis and calculations, the OTTV value is 15.6 Watt/m2. Room eligibility standards according to SNI 03-6389-2000 standards are OTTV values not greater than 45 Watt/m2. The internal cooling load is 15,010 W, the external load and ventilation is 22,688.92 W, the total cooling load is added 10% safety factor of 41.47 kW, the cooling capacity of the AC unit based on technical specifications is 45kW. The average value of air flow velocity during the air circulation test is 0.3 m/s. according to Ministerial Regulation No. 7 of 2022 maximum air circulation speed of 0.5 m/s. From several analysis and calculation results, it can be concluded that the passenger space of the CR400AF fast train trailer car is standard and feasible to operate.

Keywords: Cooling load; OTTV; CLTD; air circulation; fast train

1. INTRODUCTION

The train is a mainstay mode of transportation that is the choice of many people in their activities [1]. The large number of passenger requests prompted the government to plan high-speed rail transportation for the efficiency of changing places. This fast train will later become the first fast train in Indonesia and even Southeast Asia. The operator providing high-speed rail services for the Jakarta-Bandung connection will be PT Kereta Api Indonesia China (KCIC). The fast train facility that will be used in Indonesia later is a train facility made by the China Railway Rolling Stock Corporation (CRRC) with type CR400AF [2]. Each train will be equipped with various facilities to support passenger comfort. One of the main facilities on this fast train is the air conditioning system (AC) which plays an important role in regulating the room temperature and humidity of the passenger space during the train's operation [3]. Setting the temperature and humidity of the air is an important factor needed for passenger comfort during the trip. Factors that affect a person's thermal comfort indoors are dry air temperature, air relative humidity, surface heat radiation, air movement, activity or metabolism of a person and clothing used (SNI 03-6572-2001) [4].

Air conditioning system (Air Conditioning) is a system that regulates air circulation and air temperature in the room to maintain room humidity, so that it can provide comfort to passengers [5]. The air conditioning system used on the CR400AF fast train is Air Conditioning (AC) made by a Chinese manufacturer which is specially made, this is due to the different geometric characteristics of the countries of Indonesia and China, so a special type of air conditioner is needed that can be adapted for operations in Indonesia. The difference in these characteristics is affected by different cooling loads. This air conditioning system is designed to maintain the passenger room temperature of 22°C to 26°C in accordance with applicable regulations regarding minimum service standards in Indonesia (Ministerial Regulation No. 7 of 2022 concerning High Speed Rail Operations) [6].

The cooling load on the train is affected by the ambient temperature and the structure of the passenger compartment of the train [7]. Calculation of the cooling load can be done using the CLTD (Cooling Load Temperature Difference) method [8]. This cooling load calculation includes sensible and latent loads, including loads from outside air that passes through walls, windows, floors, roofs, and takes into account passenger loads, existing electrical equipment loads, ventilation and also infiltration [9]. In addition to calculating the cooling load, it is also necessary to plan air distribution so that all spaces can be conditioned according to their needs. Research related to this cooling load can be obtained from the calculation of OTTV (Overall Themal Transfer Value). Meanwhile, an analysis related to air circulation can be carried out by testing air circulation to determine the speed of air flow in the passenger room (SNI-03-6389-2000 and SNI-03-6390-2011) [10].

The purpose of this study was to determine the OTTV (Overall Thermal Transfer Value) value on the CR400AF fast train trailer car and to determine the calculation of the cooling load in the passenger compartment of the CR400AF fast train trailer car [11].

2. METHOD

2.1. Research flowchart

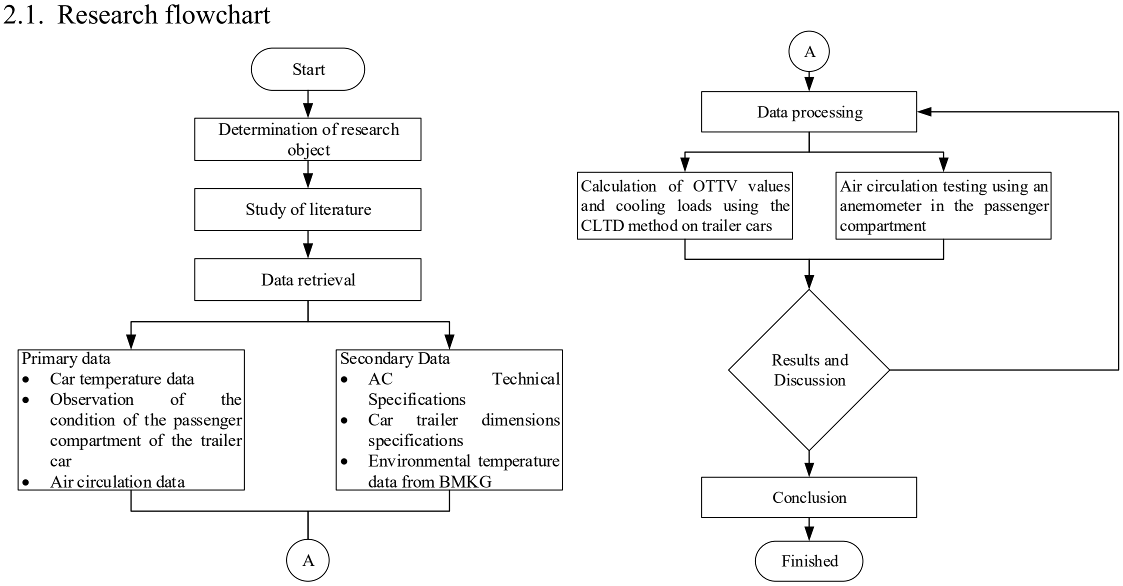

Figure 1. Research flowchart.

2.2. Research methods

This Figure 1 research was conducted by identifying problems in the object of research, then proceed with the data collection process to systematic data processing. The analysis carried out on the data obtained will be carried out according to the specified method. The data collection process carried out in this study was obtained in detail by collecting 2 types of data in general, namely primary data and secondary data according to what is needed for the process of analyzing and calculating data.

2.3. Primary data

Primary data is the main data used as material in conducting analysis and calculations in research. The primary data used in this study were obtained in the following way:

a. Retrieval of room temperature data for the CR400AF fast train trailer car.
b. Observation of the situation and conditions in the passenger compartment of the CR400AF fast train trailer car to determine the factors that influence the calculation of the cooling load.
c. Retrieval of air flow velocity testing data using an anemometer in the passenger room with windows and doors closed.

2.4. Secondary data

Secondary data is supporting data used to support calculations and analysis in research. This data can be a supporting factor in solving the problem formulation, so that the research objectives can be achieved. Secondary data used in this study, among others:

a. Technical specifications for AC (Air Conditioner) components used in the CR400AF fast train trailer car.
b. Dimensional specification of the passenger compartment of the CR400AF fast train trailer car which is also the main object of research.
c. The temperature data for the outside environment, in this case the temperature data for the cities of Jakarta-Bandung, are in accordance with data from the BMKG.

2.5. Data analysis method

The data analysis method used in this study is quantitative data analysis. This method is carried out by collecting data which is then used as a basis for calculations through various formulas to answer the problem formulation. This calculation is carried out systematically according to the required formula. In this study there are several stages for the calculation analysis.

2.5.1. OTTV calculation

Calculation of OTTV (Overall Thermal Transfer Value) in the passenger compartment of the CR400AF fast train trailer car is carried out based on SNI 03-6389-2000 standards [12]. In the SNI standard, OTTV calculations for buildings are considered to be fixed and not moving, so in this calculation the train is assumed to be stopping [13]. The technical parameters of the dimensions of the CR400AF fast train car trailer according to the specifications are as follows:

- Passenger room walls
  Train length : 18.220 mm
  Carriage width : 3.360 mm
  Train height : 3.815 mm
- Window
  Window dimensions : 1.450 x 700 mm
  Number of windows : 18 unit
  Total Window Area : 1,015 m^2 x 18 = 18,27 m^2
- Door
  Door dimensions : 800 x 2.001 mm
  Number of doors : 2 unit
  Total door area : 1,6 m^2 x 4 = 3,2 m^2

Based on the technical specifications of the trailer car above, the next OTTV calculation stage is.

- Determine the WWR value (ratio between window area and wall area)
- Determine the value of U_W
- Determine the SC (Shading Coefficient) of the wall
- Determining SF (Solar Factor)
- Calculating the OTTV value according to the formula

$$OTTV = a.\left[\left(U_w.(1-WWR)\right)\right].TD_{EK} + \left(SC.WWR.SF\right) + \left(U_f.WWR \times \Delta T\right) \quad (1)$$

2.6. Calculation of cooling load

The next step after getting the OTTV value is to calculate the cooling load. Calculation of the cooling load is carried out using the CLTD (Cooling Load Temperature Difference) method. In the CLTD method, the cooling load is calculated based on 2 factors, namely internal factors and external factors [14]. The internal factors in the calculation of the cooling load are the passenger load and the passenger room lighting load. The number of passengers is assumed to be the full number of available seats, namely 90 people. While the lighting load is calculated based on the power specifications in the technical specifications listed on the CR400AF fast train. The external factor in the calculation of the cooling load is obtained by calculating the radiation load from the glass; conduction load from the walls, windows, roof and floor of the train; as well as the calculation of the cooling load from the partition, roof and floor of the train.

2.7. Air circulation test

The air circulation test was carried out using an anemometer at the air flow source in the passenger room. The circulation test on the trailer car was carried out at 3 different points, namely points A, B and C according to Figure 2.

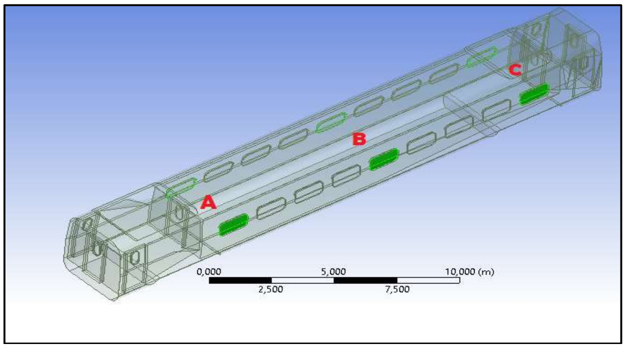

Figure 2. Air circulation test point locations.

Air circulation testing was carried out with 3 different variables, namely when the AC control was 100% cooling, 50% cooling, and AUTO. From the three different variables at 3 different points, a graph can be generated showing the air flow rate that occurs in the passenger space. The resulting air flow rate will determine whether the passenger space meets the standards stated in Minister of Manpower No. 7 of 2022.

Air circulation testing is carried out when the passenger compartment is empty or there are no people and is carried out when the train is ready to be used for operation (room temperature reaches 22-26°C).

3. RESULTS AND DISCUSSION

3.1. Calculation of OTTV trailer car CR400AF

Overall Thermal Transfer Value (OTTV) is the overall heat transfer value that is determined for the design of the walls and glass on the outside of the building. The calculation of OTTV is basically stated in the Indonesian National Standard SNI 03-6389-2000 [15]. A building is declared good if the OTTV value is not more than 45 Watt/m^2.

WWR Value Calculation

Window-Wall to Ratio (WWR) is the ratio between window area and wall area in a room.

- Wall Area (A_{Wall}) = Total wall area – Total window area (2)

  $(A_{Wall}) = (18.220 \times 3.815 \times 2)\ mm - (1.450 \times 700 \times 18)\ mm$

  $(A_{Wall}) = 139{,}02\ m^2 - 18{,}27\ m^2$

  $(A_{Wall}) = 120{,}75\ m^2$

- Window Area (A_{window}) = Total window area on the wall (3)

  $(A_{window}) = (1.450 \times 700)\ mm \times 18$

  $(A_{window}) = 18{,}27\ m^2$

- Nilai WWR: (4)

  $WWR = \frac{A_{window}}{A_{wall}}$

  $WWR = \frac{18.27}{120.75}$

  WWR = 0.1513

3.2. Determining OTTV calculation parameters

In OTTV calculations there are several parameters that are used as a reference for the calculation process, the reference value for these parameters refers to the Indonesian National Standard document (SNI 03-6389-2000) [8]. The parameters related to the OTTV calculation will later be used to calculate the OTTV value according to the applicable formula according to the Indonesian National Standard and according to the ASHRAE International Standard. To get the total thermal absorbance value, the thermal absorbance value for the building in Table *1* will be added up with the thermal absorbance value for the wall paint color in Table 2 then divided by 2.

Table 1. Radiation absorbance value against wall material.

Outer Wall Material	Thermal Absorbance Value
Heavy concrete	0,91
Red brick	0,89
Light concrete	0,86
Smooth surface wood	0,78
Exposed concrete	0,61
White tiles	0,58
Old yellow brick	0,56
White roof	0,50
White zinc	0,26
White glazed brick	0,25
Polished aluminum sheet	0,12

Table 2. Radiation absorbance value of wall paint color.

Paint the Outer Wall Surface	Thermal Absorbance Value
Evenly black	0,95
Black varnish	0,92
dark gray	0,91
Dark blue varnish	0,91
Black oil paint	0,90
Dark brown	0,88
Grey/dark blue	0,88
Blue / dark green	0,88
Medium brown	0,84
Green varnish	0,79
Medium green	0,59
Medium yellow	0,58
Medium green/blue	0,57
Light green	0,47
Semi-gloss white	0,30
Gloss white	0,25
Silver	0,25
White varnish	0,21

- α (Absorbance of solar radiation) = α total (Table 1 and Table 2)

$$\alpha = (\alpha_{alumunium} + \alpha_{cat})/2 \quad (5)$$

$$\alpha = \frac{(0{,}12 + 0{,}25)}{2}$$

$$\alpha = 0{,}185$$

- U_w (wall thermal transmittance) = 0,41 W/m^2.K
- TD_{EK} (equivalent temperature difference) = wide 126-195 m^2 (Table 3). To simplify calculations in finding OTTV values, the TDEK values for various types of construction use the values listed in **Table 3**.

Table 3. Equivalent temperature difference value for walls.

Weight / unit area (kg/m^2)	**Nilai TD_{EK}**
Less than 125	15
126-195	12
More than 195	10

- TD_{EK} = 12 K
- U_f (window thermal transmittance) = 2,89 W/m^2.K
- SC (Shading Coefficient) = Fenestration system shading coefficient.
  SC = 0,57
- SF = Solar radiation factor (W/m^2)

The average value of SF 147 for all orientations refers to Table 4 data.

Table 4. SF value based on direction orientation.

Cardinal Orientation	U	TL	T	TGR	S	BD	B	BL
SF Value	130	113	112	97	97	176	243	211

3.3. Perhitungan nilai OTTV

Calculation of the value of OTTV (Overall Thermal Transfer Value) is done using.

$$OTTV = \alpha.[(U_w.(1\text{-}WWR)].TD_{EK} + (SC.WWR.SF) + (U_f\,.WWR \times \Delta T)$$

$$OTTV = 0{,}185\ [0{,}41 \times (1\text{-}\ 0{,}1513)].\ 12 + (0{,}57 \times 0{,}1513 \times 147) + (2{,}89 \times 0{,}1513 \times 5)$$

$$OTTV = 0{,}185\ [\ 4{,}1756] + (12{,}677) + (2{,}186)$$

$$OTTV = 15{,}6\ \text{Watt/ m}^2$$

3.4. Cooling load calculation

Calculation of the cooling load in the passenger compartment of the CR400AF fast train is carried out using the CLTD (Cooling Load Temperature Difference) method. Calculation of cooling load is divided into 3 parts, namely internal load, external load, and ventilation and infiltration. Each section uses parameters in its calculations. The parameters for calculating the load will refer to the technical specifications of the CR400AF fast train and the actual conditions in the passenger compartment.

3.4.1. Beban internal

Internal loads in the calculation of the CLTD cooling load include passenger loads, electronic equipment loads, and lighting loads. The passenger load calculated in this calculation is the amount of the load that is affected by the number of people in the room. In this study, the calculation of the passenger load is assumed to be in a fully loaded passenger compartment, namely a total of 90 passengers according to the number of seats available on the trailer car train which is a second-class seat with a 2-3 seat configuration as shown in Figure 3.

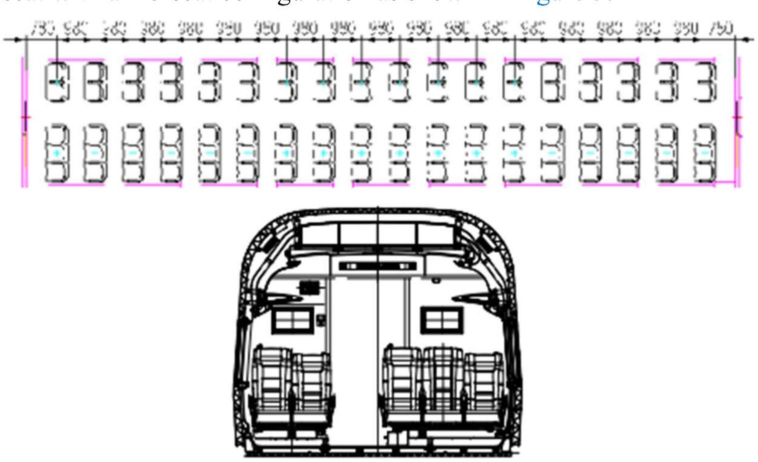

Figure 3. Second-class floor plan.

When passengers carry out activities in the passenger compartment, they will emit sensible and latent heat. The amount of sensible and latent heat that will be used for calculating passenger loads refers to the 1997 ASHRAE document, which is 70 W for sensible heat and 45W for latent heat [16].

$$Q_{penumpang} = (Q_{sensibel} + Q_{laten}) \times total\ passenger \quad (5)$$

$$= (70W + 45W) \times 90$$

$$= 10.350W$$

3.4.2. Electronic equipment load

Electronic equipment contained in the passenger room is also an influential factor in calculating the cooling load in Table 5.

Table 5. Power consumption of electronic equipment.

Total category consumption (kW)	TC01	M02	TP03	M04	M05	TP06	M07	TC08
Saloon Socket	3,2	3,2	3,2	3,2	3,2	3,2	3,2	3,2

Information:
TC = Train Cabin
M = Motor car
TP = Trailer Pantograph

The load of electronic equipment used for calculating the cooling load refers to Table 5.

$$Q_{electronic\ equipment} = 3.200W \quad (6)$$

3.4.3. Lighting load

The lighting used in the calculation of the cooling load factor is the lamp installed in the passenger compartment of the train. The amount of lighting load refers to the technical specifications of the CR400AF fast train Table 6.

Table 6. Lighting power consumption.

Total category consumption (kW)	TC01	M02	TP03	M04	M05	TP06	M07	TC08
Lighting Fittings	0,93	1,46	1,46	1,34	1,12	1,46	1,46	0,93

Keterangan:
TC = Train cabin
M = Motor car
TP = Trailer pantograph

Based on Table 6, the trailer car passenger compartment (TP03/TP06) has the total power for lighting as follows:

$$Q_{Lighting} = 1.460W$$

3.4.4. Beban eksternal

External loads in the calculation of cooling loads using the CLTD method include conduction loads from windows, roofs, walls; radiation load passing through the glass; and partition load. The conduction load is calculated as the conduction load is divided into 3 calculations:

- Window conduction load.
  U = 1,71 $W/m^2.°C$ (ASHRAE 1997 Chapter 29 Table 5)
  A = 18,27 m^2
  T_{window} = 22°C (Temperature standard, Ministerial Regulation No. 7 of 2022)
  $T_{outside}$ = 27,1°C (Jakarta's average temperature, BMKG)
  ΔT = 5,1°C

  Calculation of window conduction loads.

Q_{window} $= U.A.\Delta T$ (7)
$= (1{,}71)\ W/m^2.°C\,.\,(18{,}27)m^2.\,(5{,}1)°C$
= 159,22 W

- Wall conduction load
  U = 0,26 W/m^2.°C (ASHRAE 1997 Chapter 36 Table 3)
  A = 120,75 m^2
  T_{wall} = 22 °C (Temperature standard, Ministerial Regulation No. 7 of 2022)
  $T_{outside}$ = 27,1 °C (Average Jakarta temperature, BMKG)
  ΔT = 5,1 °C

  Calculation of the conduction load of the walls.
  Q_{wall} $= U.A.\Delta T$ (8)
  $= (0{,}26)\ W/m^2.°C\,.\,(120{,}75)m^2.\,(5{,}1)°C$
  = 160,11 W

- Roof conduction loads
  U = 0,26 W/m^2.°C (ASHRAE 1997 chapter 36)
  A = 18,22 m x 3,36 m = 61,22 m^2
  T_{window} = 22 °C (Temperature standard, Ministerial Regulation No. 7 of 2022)
  $T_{outside}$ = 27,1 °C (Average Jakarta temperature, BMKG)
  ΔT = 5,1 °C

  Calculation of the roof conduction load based on.
  Q_{roof} $= U.A.\Delta T$ (9)
  = (0,26) W/m^2.°C . (61,22) m^2. (5,1) °C
  = 81,18 W

- Total conduction load
  Q_{total} $= Q_{window} + Q_{wall} + Q_{roof}$ (10)
  = 159,33 + 160,11 W + 81,18 W
  = 400,62 W

a. Partition load
  U = 4,60 W/m^2. °C (ASHRAE 1997 Chapter 24 Table 4)
  A = 18,22 m x 3,36 m = 61,22 m^2
  T_{rc} = 22 °C (Temperature standard, Ministerial Regulation No. 7 of 2)
  T_b = 27,1 °C (Average Jakarta temperature, BMKG)

  Calculation of load based on floor partitions.
  Q $= U.A.(t_b - t_{rc})$ (11)
  = 4,60 W/m^2. °C . 61,22 m^2. $(27{,}1 - 22)$°C
  = 1.436,22 W

b. Radiation load
  The radiation load calculated in this calculation is the glass radiation load to the sun. The SCL value used is the highest radiation received by the glass (West direction, 17:00).
  Q = A. (SC). (SCL)
  T_{window} = 18,27 m^2
  SC = 0,57 (ASHRAE 1997 chapter 29)
  SCL = 545 (ASHRAE 1997 chapter 28 36)

  Calculation of solar radiation load on glass based.
  Q = A. (SC). (SCL) (11)
  = 18,27 m^2 . (0,57) . (545)
  = 5.675,58 W

3.4.5. Ventilation and infiltration loads

Overall ventilation load is obtained from the calculation of sensible load and latent load. Sensible load and latent load are then summed to get the total ventilation and infiltration load.

a. Sensible Load

$q_{sensible}$ = $(1{,}23).Q.(t_0 - t_1)$
q_{latent} = $(3010).Q.(W_0 - W_1)$
q_{TOTAL} = $(1{,}20).Q.(h_0 - h_1)$
$T_{environment}$ = 27,1 °C (Average Jakarta temperature, BMKG)
T_{room} = 22 °C (Temperature standards, Ministerial Regulation No. 7 of 2022)
Ventilasi rate (Q) = 1,800 m^3/h = 500L/s

Sensible load calculation based on.

$q_{sensible}$ = (1,23).Q.$(t_0 - t_1)$ (12)
$q_{sensible}$ = (1,23) . 500 L/s . (27,1-22) °C
= 3.136,5 W

b. Latent load

$W_{environment}$ = 0,0179 kg/kg (when temperature 27,1 °C and RH 79,2%)
W_{room} = 0,0099 kg/kg (when temperature 22 °C and RH 60%)
Ventilasi rate (Q) = 1,800 m^3/h = 500 L/s

Latent load calculation based on

q_{latent} = (3010).Q.$(W_0 - W_1)$ (13)
q_{latent} = 3010.Q.$(W_{environment} - W_{room})$
= 3010 . 500 L/s . (0.0179 – 0,0099) kg/kg
= 12.040 W

c. Total ventilation load

The total ventilation load can be calculated or by summing the sensible load $(q_{sensibel})$ dengan beban laten (q_{laten}).

q_{total} = $q_{sensibel} + q_{latent}$
= 3.136,5 W + 12.040 W
= 15.176,5 W

3.4.6. Overall cooling load

The total cooling load in the passenger compartment of the trailer car can be calculated from the sum of the internal loads, external loads, and ventilation loads that have been obtained from calculations using the CLTD (Cooling Load Temperature Difference) method [16].

Table 7. Total internal load.

INTERNAL LOAD	Rated Load
Passenger load	10.350W
Electronic equipment load	3.200 W
Lighting load	1.460 W
Total Internal Load	**15.010 W**

Table 8. Total External Load and Ventilation.

EXTERNAL LOAD	Rated Load
Conduction load	400,62 W
Partition load	1.436,22 W
Radiation load	5.675,58 W
Ventilation load	15.176,5 W
Total External Load and Ventilation	**22.688,92 W**

From calculations Table 7 dan Table 8 it can be seen that the external load has a very large role (22,688.92 W) compared to the internal load (15,010 W).

The total cooling load in the passenger compartment of the CR400AF fast train trailer car is the sum of the internal load, external load, and ventilation load, which is equal to 37,698.92 W. Based on the 1997 ASHRAE document chapter 28, the safety factor must be added at least 10% of the total cooling load . So that the total value of the cooling load in the passenger compartment of the CR400AF fast train trailer car is 41,468.81 W or it can be simplified to 41.47 kW.

3.5. Air circulation test results

Air circulation test is carried out to determine the speed of air flow when air circulation occurs in the passenger room. To achieve the expected accuracy, the air circulation test is carried out at 3 points in the passenger room according to Figure 4 and with 3 different variables, namely when the air conditioning system on the train is in 50% cooling, 100% cooling, and AUTO conditions. The results of the air circulation test according to these conditions are listed in Table 9.

Table 9. Air circulation test results.

	POINT A (m/s)	POINT B (m/s)	POINT C (m/s)
AUTO	0.36	0.34	0.29
100%	0.38	0.34	0.31
50%	0.25	0.24	0.20

The results of the air circulation test in Table 9 are listed in units of m/s. it can be seen that the highest airflow velocity is at Point A when the AC control is 100% cooling, which is 0.38 m/s. Meanwhile, the lowest airflow velocity is at Point C when the AC control is 50%, which is 0.20 m/s. The test results can be described in the graph below:

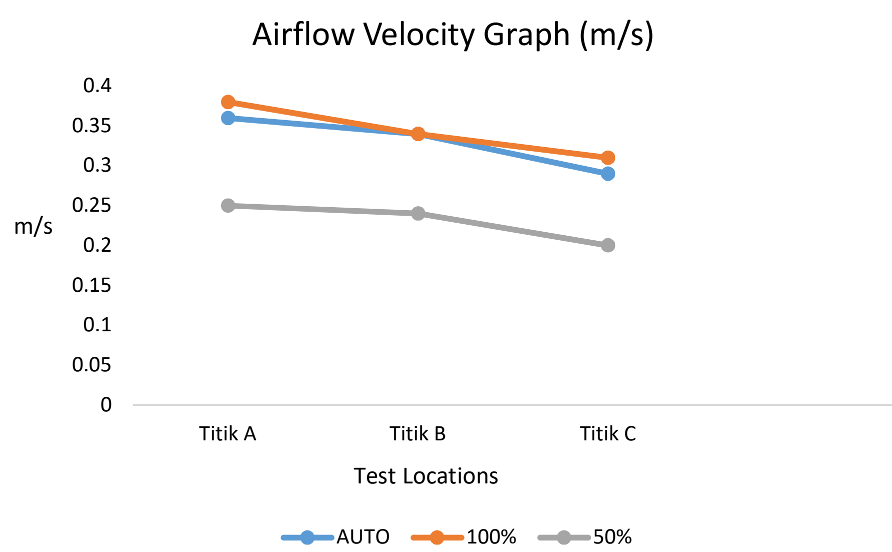

Figure 4. Graph of air circulation test results.

Based on the data from the test results in Figure 4, it can be obtained that the average airflow velocity that occurs in the passenger room of the CR400AF fast train trailer car is 0.3 m/s.

4. CONCLUSION

The calculated OTTV value of the CR400AF fast train trailer car is 15.6 Watt/m2. Referring to SNI 03-6389-2000, the room eligibility standard is an OTTV value of no greater than 45 Watt/m2. So it can be concluded that the passenger compartment of the CR400AF fast train trailer car has a good and decent design. The value of the cooling load calculated by the CLTD method is an internal load of 15,010 W, an external load and ventilation of 22,688.92 W, the total cooling load and a safety factor of 10% is 41.47 kW. The capacity of the AC unit used by the CR400AF fast train based on technical specifications is 45 kW. So it can be concluded that 1 AC unit can meet the cooling load in the passenger room. The value of air flow velocity from the air circulation test results obtained the highest value at point A at 100% cooling of 0.38 m/s, the lowest value at point C at 50% cooling of 0.2 m/s, the average value of air flow velocity at 0.3m/s. Based on Ministerial Regulation No. 7 in 2022, the maximum airflow velocity is 0.5 m/s. So it can be concluded that the passenger compartment of the CR400AF fast train trailer car meets the standards and is feasible to operate.

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