Comparison of Static Model, Adaptation Study, and CFD Simulation in Evaluating Thermal Comfort Based on Köppen Climate Classification System in Churches in Indonesia

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Highlights:

- The comfort temperature (Ta) in tropical savanna regions is higher compared to that in tropical rainforest and tropical monsoon regions.
- The high PMV score in tropical savanna regions had no effect on the perceived thermal comfort.
- The respondents' sensation of thermal comfort inside church buildings was influenced by their distance to openings, although there were differences in climate type as well as in church size and design.

Abstract. This research examined thermal comfort in church buildings in Indonesia by making a comparison between three different Indonesian climatic regions using three different research models. A static model, an adaptation study model and a CFD simulation were used to find the similarities and differences between the results generated from determining thermal comfort in church buildings in the three regions. The comparison revealed that church buildings had different PMV scores at each measuring point that were inversely proportional to the subjects' response on thermal comfort inside the buildings, i.e. points adjoining with openings affect a low PMV score and a high perceived thermal sensation, and vice versa. The CFD simulation showed that changing the conditions of the openings affects air velocity and flow into the building, which influences the subjects' thermal comfort response inside the churches.

Keywords: *computational fluid dynamics; church; thermal comfort; PMV; perception.*

1 Introduction

Comfort during church services is a factor that contributes to the congregation's concentration when worshipping [1]. Type of clothing, the time of the service,

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and activities in the service are other factors that influence the thermal comfort sensation perceived by the congregation [2,3].

Indonesian regions are classified into tropical rainforest, tropical monsoon, and tropical savanna regions. Tropical savanna regions have the longest dry season and are sparsely vegetated. These climatic characteristics influence the thermal comfort sensation people experienced when they are inside a building [4-6].

2 Research Methods

This research investigated thermal comfort in churches in three different regions in Indonesia using three different methods, namely: a Predicted Mean Vote (PMV) model, an adaptation study model, and a Computational Fluid Dynamics (CFD) simulation. The research locations were selected from academic papers published from 2000 to 2020.

3 Theoretical Framework

3.1 Thermal Comfort in the Tropical Climate of Indonesia

According to Karyono [7], compared to visual and audial comfort, thermal comfort is a more dominating physical comfort aspect. Environmental and individual factors can create the desired thermal environment [8]. Environmental factors are related to air temperature, radiation temperature, air humidity, and wind velocity, while individual factors are related to clothing, sex, age, and so on [9].

Höppe [10] states that aside from wind velocity air temperature is the environmental factor that has the most influence on thermal conditions, compared to air humidity. Meanwhile, radiation temperature has a greater impact on thermal comfort inside buildings. Moreover, the thermal conditions that occur inside a building are determined by the thermal performance of the building and the climate conditions where the building is located. Enviromental conditions influence the temperature around a building. For example, vegetation around a building has an impact on the temperature inside the building [11].

3.2 Methods of Thermal Comfort Assessment

There are two thermal comfort models that are widely applied to assess thermal comfort. The first model (PMV) is based on physical comfort, which is a more objective, universal, and measureable factor; this model is static and controlled. The second model (adaptation study) is based on psychological comfort, which is a form of unmeasurable comfort that is personal and subjective [12,13].

The third method applied in this study (CFD modeling) is commonly used in researches to predict air velocity and movement inside buildings and to replicate different scenarios for hot conditions inside a room by adjusting the wind velocity, ventilation strategy, and heat-generating tools [14].

3.3 Church

The room division in Catholic church buildings is based on the activities of the priest and the congregation. The space reserved for the priest is traditionally positioned in the front of the church, while the congregation gathers in a public area in the back of the church. This principle is still used today, with the space for the liturgical leader positioned in the front of the altar as the center of the eucharistic liturgy [15].

The interior of a Catholic church must accommodate service activities in accordance with the Catholic liturgical terms. The church service is the center of the liturgy, with Christ as the high priest, manifesting himself in the celebration of the Eucharist every Sunday around the world. Christ as the high priest is embodied in the room division/zoning, which designates the church building as a sacred space for congregation [16].

4 Discussion

4.1 Tropical Rainforest Climate

This research investigated churches in a tropical rainforest region in two places: Jakarta and Bogor (Table 1). Previous research by Karyono, *et al*. [17] in Jakarta Cathedral Church discovered that a temperature ranging between 26.4 °C and 30.4 °C (27.7 °C) was deemed acceptable by the respondents. In addition to using linear regression to determine the neutral comfort temperature, the research also attempted to examine other indicators that could influence thermal comfort, such as age, sex, activities, metabolism, and type of clothing worn by the subjects/respondents.

A previous study conducted in the Javanese Christian Church/Gereja Kristen Jawa in West Jakarta used a different method. This research employed an adaptation study model and put more emphasis on environmental factors such as air temperature, radiation temperature, and air humidity. It was concluded that the comfort temperature in the Javanese Christian Church was close to the comfort temperature in Jakarta Cathedral Church [1].

Meanwhile, the research conducted in Bogor Cathedral Church [18] discovered that the obtained effective temperature (TE) was achieved by the application of an optimal lower ventilating system.

Table 1 Research conducted in tropical rainforest climate regions.

Author and Date	Title	Method	Result	Conclusion
Karyono, T.H., *et al.* [17]	*Thermal Comfort Studies in Naturally Ventilated Buildings in Jakarta, Indonesia*	Adaptation study by observing the influence of age, sex, types of clothing and metabolism	Comfort temperature was 27.7 °C.	Metabolism has a greater effect on the thermal comfort sensation compared to type of clothing worn
Ketaren, J.M. & Karyono, T.H., [1]	*Evaluation on Thermal Comfort in Gereja Kristen Jawa (GKJ) Joglo Building, West Jakarta*	Adaptation study in addition to determining comfort temperature inside the church using linear regression	Comfort temperature was between 27.2 and 28.2 °C.	Climate factors are underlined, such as air temperature, air humidity and radiation temperature inside the church
Sekatia, A., *et al.* [18]	*Thermal Condition of Passive Cooling System in Bogor Cathedral Church*	Applying field measurement to gain efective temperature score	Adjoining zone with lower ventilation influenced the effective temperature score.	The application of a lower ventilating system influences the result from the measurement of the temperature, air humidity, and wind velocity

4.2 Tropical Monsoon Climate

Research on churches in tropical monsoon regions have mostly been carried out in Semarang (Table 2). A research on Semarang Cathedral Church revealed that an effective temperature score of around 24.95 °C was able to provide a comfortable sensation to people/subjects inside the church. Thus, the ventilation condition was proven to affect the PMV and PPD score [19,20].

The research by Dewandaru and Hardiman [21] in the Church of Saint Peter Sambiroto found that openings had an influence on the air movement and the effective temperature, where the larger the openings with wind obstacle, the lower the effective temperature score. This result is in line with the findings obtained in Bleduk Church, which had a relatively warm-comfortable PMV score that was typically influenced by seating zone, location and condition of openings, and the time of the service [2, 22].

Table 2 Research conducted in tropical monsoon climate regions.

Author and Date	Title	Method	Result	Conclusion
Sekatia, A., [19]	*The Effectiveness of Lower Ventilation towards Comfort and PMV (Predicted Mean Vote) in Cathedral Church, Semarang*	Static method (PMV) and perception	The most comfortable value was a TE of 24.97 °C	Lower ventilation (building design) is a free variable that affects both the PMV score and the subjects' response inside the church
Sekatia, A., [20]	*Predicted Mean Vote (PMV) Score in Building with Mixed-Mode Air Conditioning System*	PMV and perception	The church can be categorized as comfortable	
Carera, A. & Prianto, E., [2]	*Characteristics of Thermal Comfort in Religious Buildings, Old Town Area, Semarang*	PMV	PMV score indicates warm and uncomfortable condition	The PMV score indicates that seating zones near ventilation openings provide a more comfortable sensation
Carera, A., *et al.* [22]	*Comfortable Zone for Religious Activities in Old Town Area, Semarang*		Seating zone, condition of openings, and the time of the service are determinants of the PMV score	
Dewandaru, A.B., *et al.*[21]	*The Influence of Air Condition Design on Thermal Conditions in the Church of St. Petrus Sambiroto, Semarang*	Field mesasurement to obtain the effective temperature score	Wind velocity entering the building could lower the effective temperature score	Openings influence the air movement and lower the ET

4.3 Tropical Savanna Climate

A research in a tropical savanna region has been conducted in the St. Ignatius Loyola Sikka Church, Sikka Regency, East Nusa Tenggara. This 119-year-old church is the center and pride of the community and an important landmark in Sikka [23]. The research on this church [24] revealed that the PMV scores at each point did not match the ASHRAE standard 55-2017 value. Despite the 'mildly warm' PMV score, subjects inside the church still felt 'comfortable' to 'cool', particularly subjects wearing a sarong or traditional clothes during the service. This finding was collected from questionnaires that put sarong/traditional clothes as one of the variables in determining thermal comfort inside the church building. Figure 1 illustrates that the time of the service also had an influence on the perceived thermal sensation, while in particular wearing a sarong did not have a significant effect.

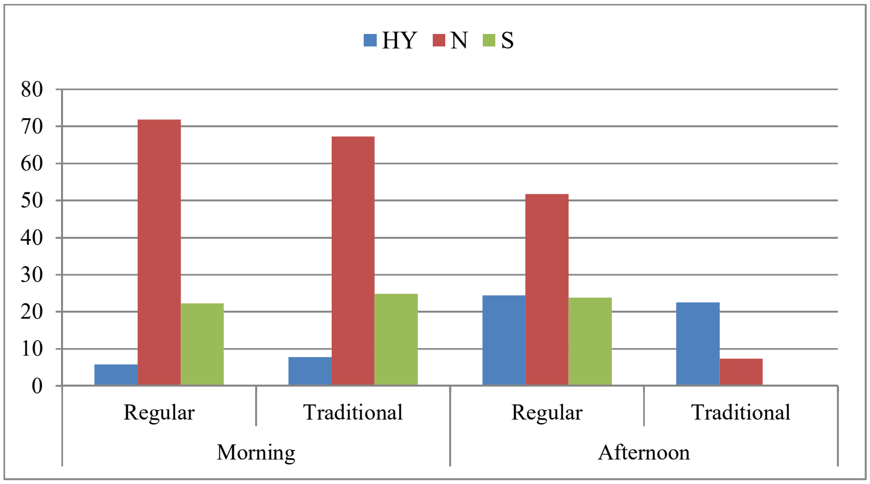


Figure 1 Respondents' perception based on clothes worn towards thermal comfort inside a church building in the morning and afternoon.

The results from the questionnaires and the PMV score were inversely proportional. This finding is in line with Karyono [25], who states that the higher the Ta and To scores, the wider the differences between the respondents' opinions and the PMV scores. Based on the time of the service, the respondents attending an afternoon service felt warmer compared to the respondents attending a morning service. Kaharu, *et al.* [26] noted that the dissimilarity between the PMV score and the respondents' response on thermal comfort could be affected by when and where, i.e. the time of the service and the place inside the church when the measurements were taken.

The PMV scores showed that the factors that influence thermal comfort were: climatic factors, type of clothing, and human activities. In addition, the respondents' responses indicated that type of clothing (formal sarong or regular formal clothing) had no influence on thermal comfort. This was evident from the perceived sensation when wearing regular formal clothing or a formal sarong during a service. Factors that influence how people dress are year-round climate and season, different thermal conditions inside the room, age, and sex [27].

Respondents worshiping at Church of St. Ignatius Loyola considered wearing a sarong or lipa to be more comfortable due to fabric's thickness, where the thicker the fabric, the softer sarong. A softer fabric provides a 'cooler' sensation when worn (Figure 2). This finding was analyzed using Das & Alagirusamy's concept of clothing comfort, stating that clothing comfort can be rated on psychological-cultural and psychological-physical (stiff, soft, hard) scales to express skin sensations and visual sensations from fabrics [28]. Respondents are asked to assess the quality of the fabrics they wear using simple and easy to understand pairs of words.

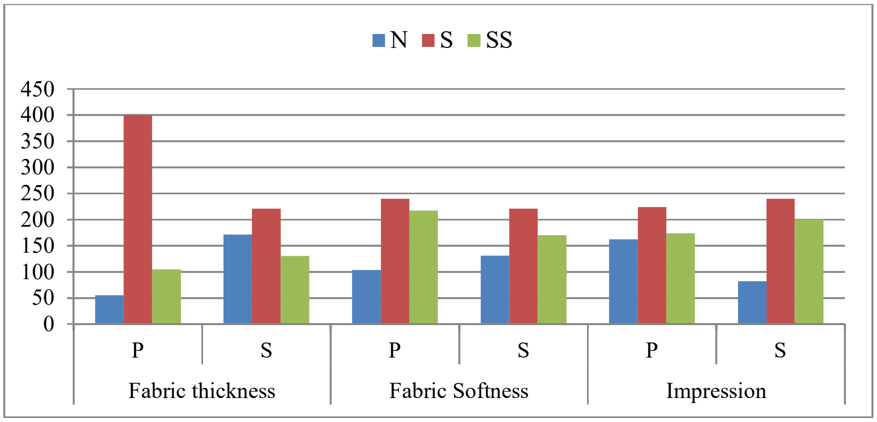


Figure 2 Response to wearing sarong as formal clothing.

After obtaining the result from the PMV and the adaptation study method, further testing with a CFD simulation was carried out to decide the climatic factors that most influence thermal comfort inside church buildings.

The CFD simulation aimed to determine the wind flow distribution with opened doors and closed windows, closed doors and opened windows, or opened doors and windows. The result showed that the same wind flow distribution occurred in areas with opened doors and windows. This implies that a geometry with opened doors and windows was appropriate to simulate the south, east, and west wind direction distribution.

A geometry with closed doors and opened windows was appropriate to simulate the temperature distribution when the simulation tried to observe the effect of heat transfer on the church walls. In the CFD simulation, mesh was made using polyhedral meshes, which allows a polyhedral shape and customization of details to simplify objects to making them more effective and efficient due to the low number of elements and the high number of interfaces (Figure 3).

The Computational Fluid Dynamic software was used with the following settings:

1. *Turbulence: k-epsilon realizable*
   The k-epsilon equation is a semi-empirical model equation with two equations that can independently determine the turbulent velocity and length

scale. This model is often used for fluid flow simulation processes and heat transfer involving rotation, separation, recirculation, and boundary layer flow with large pressure gradients.

2. *Speed and temperature inputs*
   This simulation used unvarying external speed and temperature inputs of 1.545 m/s and 29 °C taken from the average of wind velocity in the field. The value change would have no effect on the existing wind pattern as long as it was still in the same flow regime.
3. *Materials selection*
   This research used materials adjusted to the field conditions in church buildings. The simulation used two materials to observe the different effects from materials use, namely: 1) materials found in the field, and 2) materials with high conductivity (alumunium). Other unmentioned settings in this study indicate unchanged default settings to maintain a conservative climate solution level. Each of the wind flow characteristics was analyzed using wind velocity contour plots and wind distribution plot data as illustrated

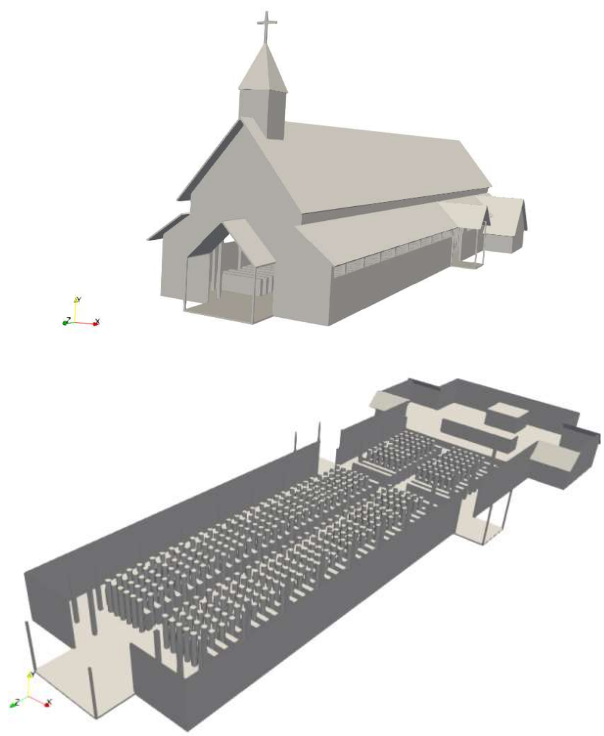
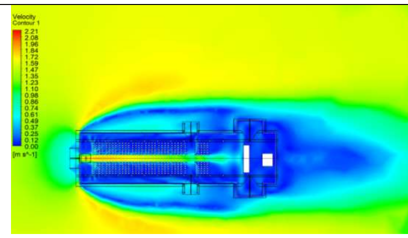
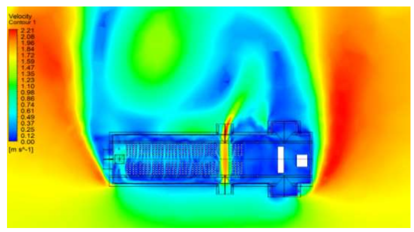
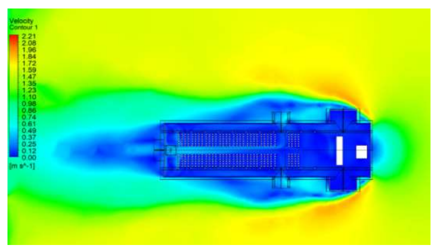


Figure 3 Church exterior (above) and church interior (below).

Table 3 Research conducted in tropical monsoon region.

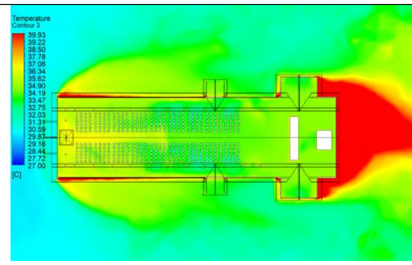
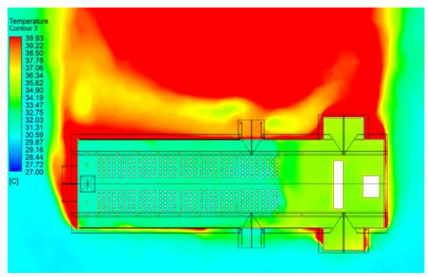
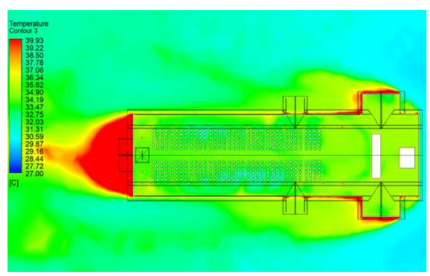
Wind velocity contour plot with wind from the west	
Wind velocity contour plot with wind from the south	
Wind velocity contour plot with wind from the east	

The simulation revealed the following:

1. Wind velocity contour plots with three wind directions showed differences in the distribution of wind velocity inside the church building.
2. Wind from the south has a more even distribution than wind from the other two directions. This can be seen from the distribution of the light blue contour in Table 3b, which indicates that a wind velocity of around 0.5 m/s occurs due to the location of the church windows, which directly face the direction of the wind so that they are effective in distributing wind to all parts of the church.
3. Wind from the east has an uneven distribution because the wind directly hits the back wall of the church, causing wind separation and making it hard for the wind to enter the church spaces either through doors or windows.
4. Table 3 shows the effect of wind from the west with opened doors. The effect was only significant on a straight line alongside the church's main doors marked with yellow plots with a maximum wind velocity of 1.8 m/s.

Table 4 shows that the lowest temperature occurs at a distance of 1 meter from the temperature line starting from the bottom with a value of 30.08 °C. The highest temperature occurs at a distance of 19 meters with a value of 33.5 °C. The average error obtained from sample collection was 8.43%, which could have happened due to the effect of sun radiation on the ambient temperature.

Table 4 Influence of the use of field materials in church building.

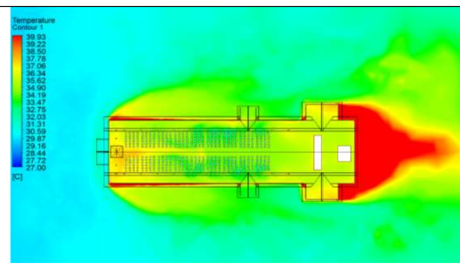
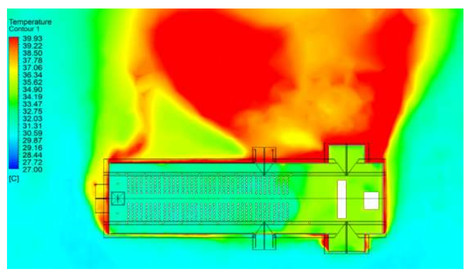
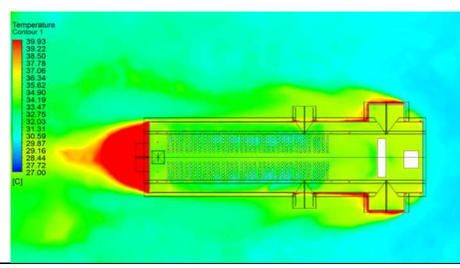
Temperature distribution with wind from the west using field materials	
Temperature distribution with wind from the south using field materials	
Temperature distribution with wind from the east using field materials	

To complete this research, Table 5 shows the influence of the use of high conductivity materials in church buildings.

The influence of using of high conductivity materials in the church building:

1. Comparing Tables 4 and 5 shows that the difference of the conductivity of the materials affects a temperature increase from 34 °C to 35 °C in the pulpit area, while there was no significant temperature change in the areas near windows and doors. This result indicates that the shape (or the availability) of windows and doors is quite significant in making the temperature uniform in the surrounding areas. Hence, using high conductivity materials only affects a temperature rise of 1 °C in areas with no windows or doors.
2. Tables 4 and 5 also shows the more dominant effect of shape, where a temperature difference occurs in areas with no windows or doors. This condition also influences the PMV score, which is lower in areas close to openings compared to areas far from openings.

Table 5 Influence of the use of high conductivity materials in church building.

Temperature distribution with wind from the west using high conductivity materials	
Temperature distribution with wind from the south using high conductivity materials	
Temperature distribution with wind from the east using high conductivity materials	

To validate the simulation results, the temperature distribution was taken along a straight line of 19 meters long. The line started 4 meters outside the church door and was set at a height of 1.5 meters, as illustrated in Figure 4.

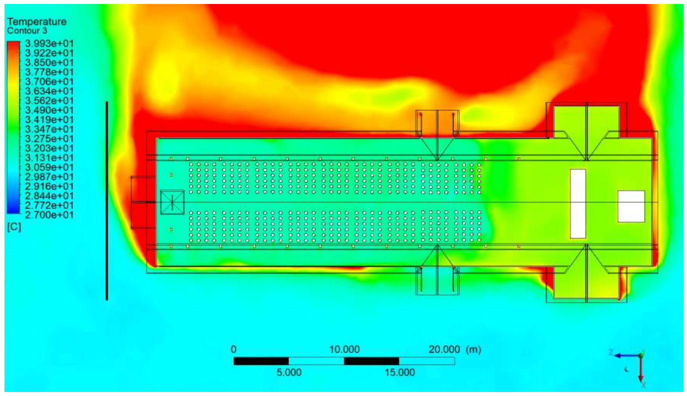


Figure 4 Temperature line on the south wind contour.

Table 6 shows the results of the temperature distribution along this straight line.

Table 6 Temperature distribution along straight line.

Distance [m]	Temperature [C]	Avg. Field Temperature [C]	Error [%]
0	30.14	29	3.94
1	30.08	29	3.74
2	30.14	29	3.93
3	30.18	29	4.06
4	30.12	29	3.85
5	30.24	29	4.29
6	30.22	29	4.19
7	30.36	29	4.68
8	30.54	29	5.32
9	31.22	29	7.66
10	31.69	29	9.29
11	33.05	29	13.95
12	33.44	29	15.31
13	33.50	29	15.53
14	32.75	29	12.92
15	32.49	29	12.03
16	32.08	29	10.63
17	32.02	29	10.40
18	32.11	29	10.71
19	32.55	29	12.26
		Avg. Error	8.43

Figure 5 shows the results of the temperature distribution along the straight line. The CFD simulation demonstrated that openings (doors and windows) have an effect on wind flow into the building, where a high or low wind velocity affects the temperature score and causes conditions that are perceived as 'comfortably-warm' to 'warm'. This result indicates that wind could be one of the most determining factors towards the level of thermal comfort in PMV, while the shape of the building influences the temperature scores inside the building. Moreover, in terms of perception, clothing (fabric thickness) does not influence the comfort felt inside the building (ranging from comfortable to uncomfortable), but rather is one of the factors that contribute to feeling comfort inside the building.

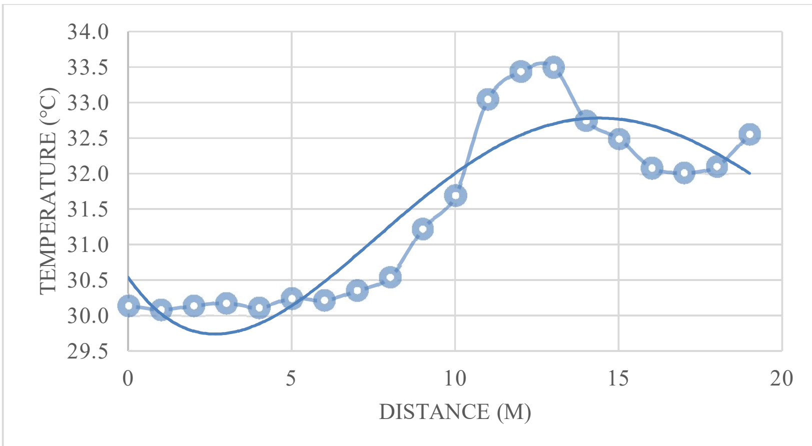


Figure 5 Temperature vs distance graph.

5 Conclusion

Regardless of the time differences in each church in the different areas, it was evident that the PMV scores were inversely proportional to the subjects' perceptions. In the tropical savanna climate region, a high PMV score had no relation to the perceived thermal sensation response. The highest comfort temperature value in tropical savanna climate regions was relatively high (up to 1-2 °C) compared to the other two climatic regions. It was discovered that clothing insulation had no effect on the subjects' response inside the church building.

The similarities in the results of the two models used were: the condition of openings (closed or opened) had an impact on the performance of the thermal comfort inside the building, as this further affected the PMV score as well as the responses of subjects who were seated near openings.

Evidence from the CFD simulation showed that the closer the distance of openings in opened condition to the point/zone of the subject, the higher the perceived comfort score of the room. This the result of direct contact between wind flow and human skin, which instantly provides a different thermal sensation compared to without direct exposure to wind flow. Further study could highlight the influence of wearing a formal sarong in tropical savanna regions on thermal comfort inside church buildings.

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