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IMPROVING THERMAL COMFORT OF WORKERS IN THE FINISHED GOOD WAREHOUSE BASED ON PREDICTED MEAN VOTE (PMV) USING COMPUTATIONAL FLUID DYNAMICS (CFD)

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Abstract The hot and humid tropical physical work environment is one of the factors causing the high heat stress and potentially influence greatly to the worker performance in a company. The aim of this paper is to optimise the workers thermal comfort based on personal and environmental condition in finished product warehouse on tropical climate. The first step of the research is a study of literature on Predicted Mean Vote (PMV), Computational Fluid Dynamic (CFD) and human thermal comfort. The researchers conducted data collection on thermal comfort outside and inside the warehouse on the existing conditions, namely; temperature, activity type, clothing, air velocity, Mean Radiant Temperature (MRT), and relative humidity. Existing data are used to calculate PMV and Predicted Percentage of Dissatisfied (PPD) at 44 workers activity points with PMV results in the range of +2.27 to +2.61 with average + 2.38 (warm) and PPD in the range of 88.7% to 95.4% with average 94.41%. The CFD simulation was employed to illustrate the contour plot of temperature distribution, relative humidity and wind velocity on existing and after improvement conditions. The simulation tests show that temperature and air speed were the important factors of improving PMV in this problem. Potentials due to temperature differences in outdoor and indoor at 4^0C became the basis for the improvement of the warehouse building. It was conducted by installing 33 exhaust fans with a capacity type of 3610 m^3/h. The improvement is capable to lower the average value of PMV to +1.63 and average PPD 58.58%. It can be conclude that the thermal comfort improvement should be focused just only on six factors of PMV formulation.

Keywords Thermal Comfort; heat stress; predicted mean vote (PMV); predicted percentage of dissatisfied (PPD); computational fluid dynamic (CFD).

1. INTRODUCTION

The physical work environment is one important factor which influences comfort and work performance [1]. Although the human body system has an adaptive psychological mechanism, in which the mechanism can allow our bodies to tolerate the physical work environment conditions over a range, climate often has adverse effects on the body [2]. Losses that affect the body would also affect and interfere with work performance. To avoid this, it is necessary to adjust the physical work environment with the type of work performed in an endeavour to obtain stable or improved performance. Thermal comfort is one of the physical work environment factors with potential significant effect on a worker's productivity [3]. Thermal comfort can be defined as a condition that indicates a person's satisfaction or comfort with the thermal working environment [4]. Some factors which may affect the thermal conditions in the working environment are humidity, air velocity, and temperature. Overly high or low working temperature conditions decreases one's comfort. As an

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example of the work environment is the overcooling of offices in the tropics caused by social and psychosocial factors affecting energy use [5]. The thermal discomfort is exhibited from the increased LF/HF in Heart Rate Variability (HRV) [6]. In addition, clothing conditions used by workers also give effect to the thermal potential felt by workers. Using clothing such as hybrid Personal Cooling Garment (PCG) may help a worker in obtaining thermal comfort [7]. Under such conditions, despite workers being capable to adapt to their environment, they prefer low environmental temperature could be increased to a normal temperature range (Wang, 2018). In addition, an increase in job demand accompanied by temperature changes may cause cognitive load [8]. Some heat-related states such as heat stroke, heat exhaustion, heat syncope, heat cramps, heat rash, and transient heat fatigue can occur due to excessive high-temperature exposure [9].

Based on the standards set by SNI 03-6572-2001, temperatures suited to Indonesian human comfort range from 20.5°C to 27.1°C [10]. If room temperature is not in accordance with set standards, workers can quickly experience heat stress. Heat stress can cause workers to experience fatigue faster. Worker fatigue can adversely affect productivity. There are many effects of fatigue. It is a major factor which may cause accidents, especially industrial accidents [11]. The extent of one's fatigue can affect human performance from a trivial level to extremely dangerous.

Food flavouring companies have several activities consisting of food seasonings production such as procurement, production, packaging, and delivery. Procurement, production and packaging activities occur in the same building, while the process finished goods storage occurs in the Finished Goods Warehouse. There are several processes occurring in the warehouse such as reception, storage, and delivery of goods. The process of product delivery of food seasoning Production Company is divided into two, domestic and overseas delivery (export). In the process of shipping abroad, there are 17 workers who have a work schedule for 8 hours starting from 7:00 to 15:00. There are several export process that must be executed, among others, the unloading process in the form of guarantee between the container number and the goods to be sent, the loading process in the form of export product delivery. There are 22 male workers in warehouse worker including 2 team leaders, 3 people of administration, and 17 workers specialized in the delivery. The warehouse is divided into 4 parts namely warehouse 1 and 2 to store materials, warehouses 3 and 4 to store finished goods (products). To obtain good product quality there are some things that need to be considered such as room sterilization to prevent foreign material, especially insects coming from outside environment. During the production process, room temperature must be ranged between 16 ^{o}C-23 ^{o}C. Based on observation conducted, it was found that the room temperature ranged between 32-33^{o}C in the morning, and at noon can reach 35^{o}C.

Efforts that can be done to improve thermal comfort is to conduct engineering and administrative control on the warehouse. The use of a CFD simulation can help to identify the fluid flow present in the Finished Goods Warehouse, therefore areas requiring improvement are obtained. After performing an improvement simulation, an estimated recalculation of thermal comfort felt by the employee was conducted. When the thermal comfort of workers increases, there will be a decrease in the risk of heat stress that will affect the productivity of workers in the Finished Goods Warehouse belonging to food seasoning company.

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2. MATERIALS AND METHODS

Thermal comfort commonly was divided into two main factors, namely individual or personal factor (clothing insulation and metabolic rate) and thermal environment factor (average air temperature, relative humidity, mean radian temperature and relative air velocity) [12,13,14]. This two factors combined together to formulated and then to predicted the level of human thermal comfort or called Predicted Mean Vote (PMV).

2.1. Predicted Mean Vote (PMV)

Predicted Mean Vote (PMV) is an index used to predict the overall thermal comforts felt by people in large groups [15,16]. The PMV model exhibits that thermal comfort can be described as a function of the thermal load on the effector mechanism of the human thermoregulatory system. Under normal environmental circumstances, the human thermoregulatory system will automatically modify skin temperature and sweat secretions to maintain the body's heat balance. PMV value determines the range of temperature sensations that people perceive their surroundings. This PMV index ranges between -3 (very cold) to +3 (very hot). The PMV equation can be used when activity (metabolic rate) and clothing (thermal resistance) are estimated, and some environmental parameters such as air temperature, mean radiant temperature, relative air velocity, and relative air humidity are measured directly [17,18]. Factors used in the calculation of PMV are as follows:

1. Body metabolism
2. Clothing insulation
3. Air temperature
4. Mean radiant temperature
5. Air velocity
6. Relative Humidity

Equation 1 is an equation used to calculate PMV value [15] with the condition of the room which does not get direct sunlight radiation. Equation 2 to equation (4) aids in calculating PMV.

$$PMV = (0.303e^{-0.036M} + 0.028)\{(M-W) - 3.05x10^{-3}x[5733 - 6.99\,(M-W) - p_a] - 0.42x[(M-W) - 58.15] - 1.7x10^{-5}M(5867 - p_a) - 0.0014M(34 - t_a) - 3.96x10^{-8}f_{cl}x[(t_{cl}+273)^4 - (MRT + 273)^4] - f_{cl}h_c(t_{cl} - t_a)\} \quad (1)$$

$$t_{cl} = 3.57 - 0.028\,(M-W) - I_{cl}\{3.96\times 10^{-8}f_{cl}[(t_{cl}+273)^4 - (\bar{t_r}+273)^4] + f_{cl}\times h_c \times (t_{cl} - t_a)\} \quad (2)$$

$$h_c = 2.38\,(t_{cl}-t_a)^{0.25} \text{ for } 2.38\,(t_{cl}-t_a)^{0.25} > 12.1\sqrt{v_{ar}}$$
$$h_c = 12.1\sqrt{v_{ar}} \text{ for } 2.38\,(t_{cl}-t_a)^{0.25} < 12.1\sqrt{v_{ar}} \quad (3)$$

$$f_{cl} = 1.00 + 1.290\,I_{cl} \text{ for } I_{cl} \le 0.078\,m^{2\,o}\mathrm{C/W}$$

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$$f_{cl} = 1.05 + 0.645\, I_{cl} \text{ for } I_{cl} > 0.078\, m^{2\,o}\mathrm{C/W} \tag{4}$$

Where:
PMV = Predicted mean vote
M = the metabolic value of the body surface area (W/m^2)
W = external activity = 0 for most activities (W/m^2)
I_{cl} = clothing thermal durability (m^2K/W)
f_{cl} = the ratio of the covered and uncovered surface area.
t_a = air temperature (^{0}C)
$\bar{t}_r$ = average radiant temperature (^{0}C)
v_{ar} = relativity air velocity (m/s)
p_a = partial water vapour pressure (Pa)
h_c = convective heat transfer (W/m^2K)
t_{cl} = clothing surface temperature (^{o}c)

Predicted Percentage of Dissatisfied (PPD) is a derivative of PMV that predicts the percentage of people who are not thoroughly satisfied from a large number of people [15,19]. When the value of the PMV is known, PPD value can be calculated using Eq (5). For the condition of the room with direct sunlight radiation, there is an adjustment of the equation to calculate PPD value.

$$PPD = 100 - 95 \times e^{-(0{,}03353 \times PMV^4 + 0{,}2179 \times PMV^2)} \tag{5}$$

2.2. Computational Fluid Dynamic (CFD)

Computational fluid dynamics (CFD) is a method of calculation with a control of dimensions, extent, and volume by utilizing computer computing aids to perform calculations on each element of the divisor [20]. The principle of CFD is a space containing fluid divided into several parts, this is often called the cell and the process is called meshing. Each control points will be calculated by the application using determined domain constraints and boundary conditions. This principle is widely used in the calculation process using the help of computer computing.

In general, CFD calculation process consists of 3 main parts which are preprocessor, processor, and post processor.

1. *Preprocessor*

At this stage, data input ranges from defining the domain as well as defining boundary conditions or boundary conditions. In addition to boundary conditions, this stage defined heat sources. For heat sources that enter through the galvalum surface, it can be calculated using Equation 6. The following is a calculation of heat transfer through the galvalume surface [21], [8].

$$q = \Delta T \text{ x h} \tag{6}$$

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Where
q = the intensity of the heat transfer of sunlight through the galvalume surface
ΔT = the temperature difference between the inside and outside the building
h = value of material conductivity

According to Binarti and Satwiko [22], in the determination of good air ventilation, there are several things to note including the room volume and air change rate which can be found in equation 7.

$$Q = V \times ACH \qquad (7)$$

Where:
Q = ventilation capacity
V = room volume
ACH = Air Change Rate (4,5 t/h= determination for warehouse)

Required ventilation area:

$$A = Q / v$$

Where:
A = Required ventilation area (m^2)
Q = Ventilation capacity (m^3/h)
v = air velocity (m/s)

2. *Processor*

At this stage, the process of calculating the input data with the equations involved iteratively was conducted. This means that the calculation was conducted until the result to the smallest error or until it reaches a converging value. The calculation was conducted thoroughly to the volume control using the integration of discrete equations process.

3. *Post processor*

At this stage, the results of the calculations are interpreted into images, graphics, even animations with certain color patterns. Figure 1 is an example of the post processor stage results on PMV values distribution in a room. PMV value is exhibited based on the existing color in the room.

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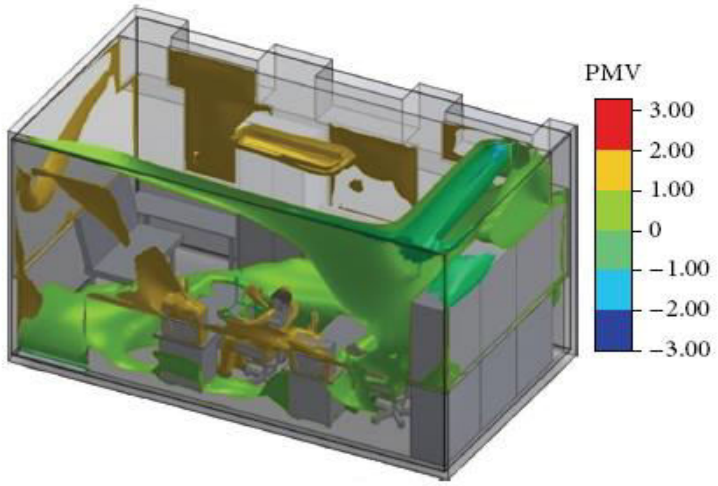

Figure 1. An example of post processor stage results (according to Chou).

2.3. Research Methods

The main goal of the research is to optimise workers thermal comfort in finished product warehouse related to six factors, including cloth isolation, metabolic rate, relative wind speed, air temperature, relative humidity and mean radiant temperature. Understanding the existing condition of warehouse design from the point of thermal comfort view is very important in the research. To supervising this problem, descriptive research methodology is employed. Descriptive research show how to explore, clarify, and interpret the thermal comfort phenomena. Primary data is data obtained directly from the object of research and observed in place of research implementation. Data obtained by observation and interview. Observation is used to determine the activities of workers as a reference in determining the metabolic rate values of the body (met) and uniforms used by workers as a reference in determining the value of clothing insulation (clo). Data of environmental parameters of air temperature (°C), air velocity (m/s), and relative humidity (%) in the workplace were measured using multifunctional air Velometers. Secondary data is data that has been available or has been presented by the company as the research site. Secondary data used in this research include workers condition and company layout.

Figure 2 describes the steps of the research, including collecting data, calculating PMV index, PPD and the solutions of the workers heat stress in product warehouse area. First step is collecting the existing data of PMV factors in every workers place. From the PMV data, the PPD existing can be predicted using equation 5. The next step is modelling warehouse in 3D CAD model and tested by using CFD simulation test to describe the existing situation of air velocity distribution, air temperature and relative humidity contour. Validation process was employed by comparing PMV value from primer data collecting and PMV value from CFD simulation. If the average PPD value is bigger than 20%, the existing warehouse condition should be modified. I this case, the CAD model and CFD simulation are the key factors in improving the thermal comfort of warehouse workers.

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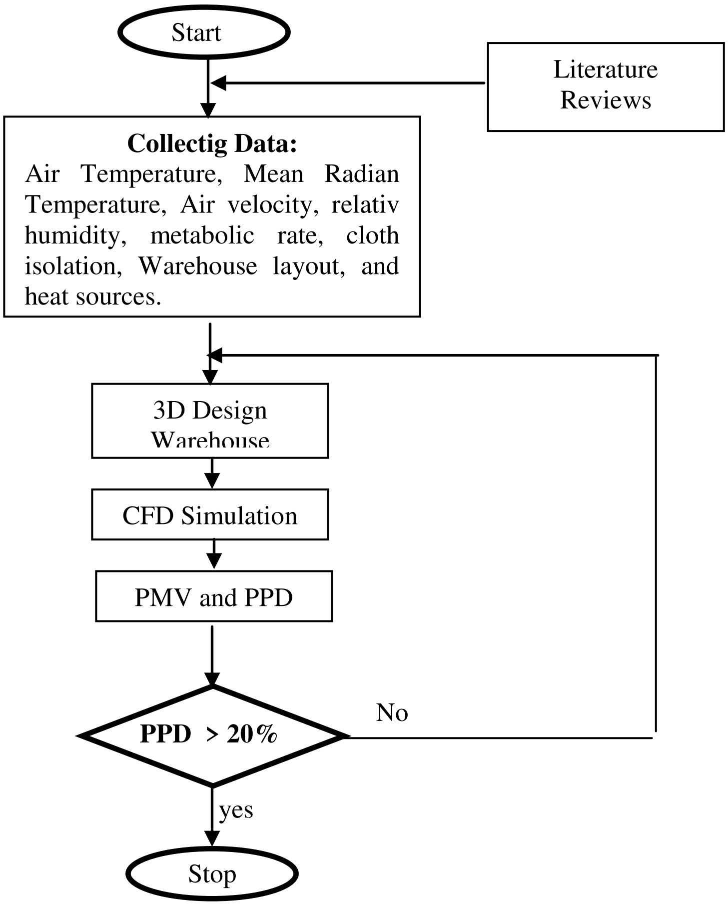

Figure 2. Flowchart of research steps for looking for workers thermal comfort.

The object of the research is a finished goods warehouse with area of 2450 m^2 for a height of building = 7 m. Figure 3a describes the layout of finished goods warehouse consists of 2 main warehouse. Warehouse 1 has 1400 m^2 area, while warehouse 2 has 1050 m^2 area. Measurement of environmental data that includes air temperature, air velocity, and relative humidity was conducted at an altitude of 1.1 meters above ground level. Environmental data retrieval observation points are locations where workers are often visited by other workers for their activities. In this study, the location of the measurement amounted to 44 observation points. The data were collected from 9 am to 11 am according to ASHRAE guiding. The assessment of workers activity metabolic rate is assessed based on observations of the activities carried out by workers for 30 minutes to 1 hour. Clothing insulation data is obtained from every clothing item used by workers in the finished goods warehouse. Clothes used by workers in the finished goods warehouse are uniforms consisting of short-sleeved clothing, thin material trousers, underwear, ankle socks, and shoes (see figure 3b).

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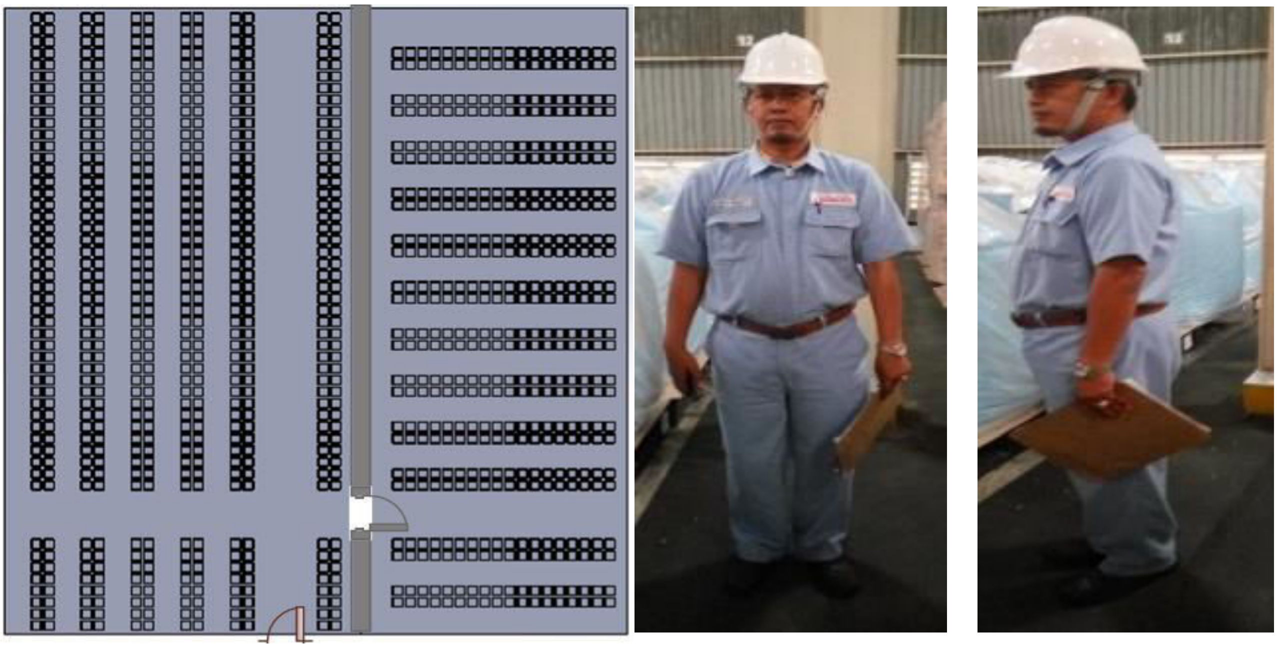

Figure 3a. Layout of finished goods warehouse, b. Worker's uniform.

3. RESULTS AND DISCUSSION

3.1. Heat Stress for Existing Condition

The workers' heat stress assessment was conducted using the Predicted Mean Vote (PMV) index. The first step taken to assess the existing of PMV index is to assess the clothing insulation, metabolic rate, relative wind speed, air temperature, relative humidity and mean radiant temperature. Following is the analysis of the existing PMV factors:

- **Clothing insulation**: Assessment of clothing insulation is based on each item of clothing worn by the worker. The value of the clothing insulation is expressed in clo units. The total insulation value is 0.81 clo which is coming from underwear = 0.04 clo, uniform = 0.49 clo, trousers = 0.24 clo, length socks = 0.02 clo and shoes = 0.02 clo.
- **Metabolic rate:** The metabolic rate or worker metabolism rate is calculated based on the activities performed in 1 hour. Warehouse workers activities are standing and talking produces (1.2 met), driving forklift = 1.5 met, lifting product = 1.2 met, walking = 2.0 met, and reading and moving product file code = 1.4 met. As a result, the average of workers metabolic rate is 1.46 met.
- **Air temperature** in 44 places have average = 32.77 ^{o}C, as a big warehouse and steady from the Sun light intensity during observation then the **mean radian temperature** is assumed same with indoor air temperature = 32.77 ^{o}C.
- **Average relative air humidity** = 40.47% and **average wind speed** = 0.028 m/s.

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According to the data and using equation 1, it can be calculated that the average of PMV existing is 2.38 or categorised in warm condition. Moreover, by using equation 5, the Predicted Percentage of Dissatisfied (PPD) can be determined as 91 %. It means that 91% of warehouse workers are not satisfied with thermal condition. The worst PMV existing is 2.61 at point 24. The warehouse workers need better thermal level by innovating air conditioning, air circulation or modifying the building.

The Computational Fluid Dynamic (CFD) was employed to validate the 3D CAD model with the existing condition. Based on the existing observation, the PMV factors of air temperature, wind speed and relative humidity are used as input the simulation model. Analysis type used is a type of internal analysis. Earth gravity considerations are taken into account and are based on the Y axis of the 3D CAD model. The next process is defining the boundary conditions of the finished goods warehouse. Factors defined in the boundary conditions include the air inlet and outlet in the finished goods warehouse. According to the data report, average air velocity on the inlet door is 0.231 m/s with temperature 29°C and relative humidity = 50%. The next process is to define the heat source in the finished goods warehouse, lamp produced 55 watt and ceiling area produced 30,306,8 watt. After determining general setting, boundary conditions, and heat sources, the following steps involved meshing or dividing the finished goods warehouse into a certain amount of grid. In this study, the level of initial mesh used is level 3. Level 3 initial mesh divides the finished goods warehouse into 52 parts on the X-axis, 4 parts on the Y-axis, and 16 parts on the Z axis. The following process is processor stage. At this stage, CFD simulation will be run based on the model. Running Finished Goods Warehouse model was conducted based on inputs previously defined at the preprocessor stage. The interpretation of the CFD simulation is illustrated by a cut plot or flat field piece. The cut plot used is a cut plot with a height of 1.1 meters from the Y-axis. Figures 4 shows the distribution contour of air temperature. It can be concluded that there is no significant difference of air velocity, relative humidity and air temperature between field measurement and CFD test results. As a consequence, the 3D CAD model can be used to test the warehouse modification.

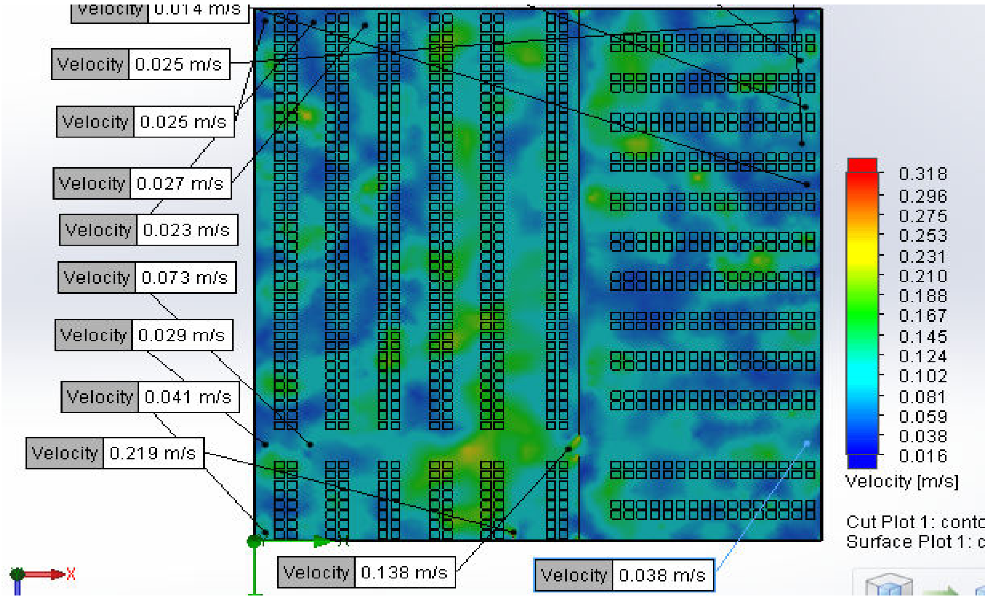

Figure 4. Temperature distribution for existing condition.

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3.2. Reducing Heat Stress Based on CFD Simulation Test

According to existing condition, the average workers PMV value in the finished goods warehouse currently indicate the occurrence of heat stress with moderate to strong level, therefore it is necessary to make improvement recommendation in order to prevent human error occurrence. This improvement recommendation aims to reduce PMV value as well as potential heat stress experienced by workers. Improvement recommendation suggested in this research are administrative control and engineering control. Administrative control in the finished goods warehouse is in the form of the clear division job description to lessen worker workloads. For example, checking goods code and driving activities are delegated to different workers.

Engineering control conducted in an endeavour to improve external factors such as temperature, air velocity, and relative humidity. Air velocity and moisture are closely related to the large temperature present in an area. There are several factors causing the high magnitude of the PMV value. Those are air temperature and conducted the activity. Based on the observation data, the high-temperature values due to lack of good air circulation cause 4 ^{o}C difference between the warehouse indoor and outdoor. CFD simulation is used to provide a recommendation in engineering control. There are several actions that could be conducted in reducing warehouse's temperature, such as adding exhaust fans, ventilation and use of air conditioning. Recommendation to be simulated is to increase air circulation by installing exhaust fan with a capacity of 3610 m^3 / h. The use of air conditioning is not recommended because the cost is high and can damage the products in the Finished Goods Warehouse.

Based on the layout data of warehouse and distribution temperature / wind speed in existing condition, the recommendation are adding 33 exhaust fans. Figure 5 explains the CFD test results of temperature distribution after exhaust fans were implemented in the of warehouse building. According to the test, the temperature is obtained at 29.21 ^{o}C to 29.88 ^{o}C, the air speed = 0.013 m/s to 0.22 m/s, and relative humidity = 46% to 49%. The air speed is categorised in ISO 7730 (1994) standard which is less than 0.4 m/s. The results show that after improvement recommendation, PMV and PPD value decreases in all observation points. In the existing condition, PMV value is in the range of +2,4 to +2,61, whereas PPD value is in the range of 91,2% to 95,4% it indicates that finished goods warehouse workers have potential to experience moderate to strong heat stress and discomfort at 91.2% to 95.4% range. Compared to the conditions after adding 33 units of exhaust fan with a capacity of 3610 m^3 / h, PMV and PPD value fell significantly. The PMV value after the improvement implementation is in the range of +1.25 to +1,8 with an average value of 1.60, while PPD value is in the range 38.08% to 67.31% with an average value of 56, 88.

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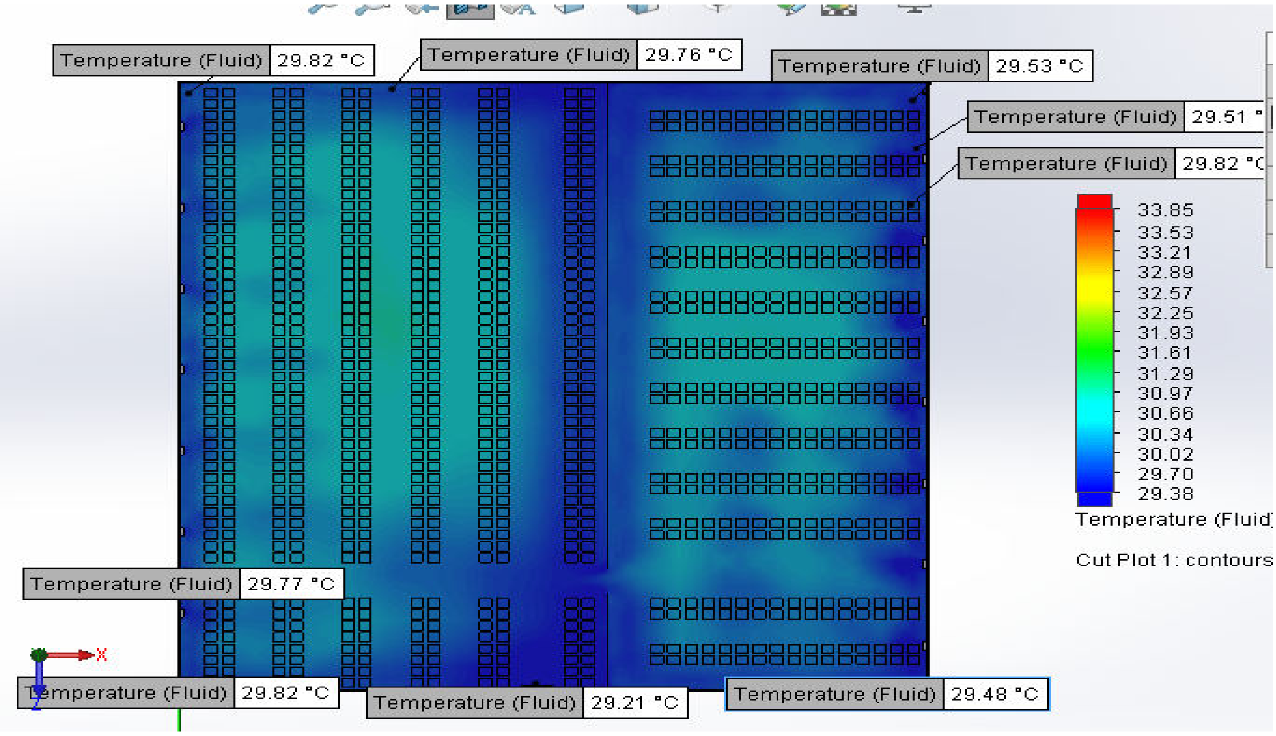

Figure 5. Temperature distribution for recommendation model, installing exhaust fan.

4. CONCLUSIONS

The research successfully employed the CFD simulation test to innovate the workers‘ thermal comfort in warehouse building. In the existing condition, the PMV ranges at +2.27 to +2.61 with the average value of +2,38, whereas PPD value is in the range of 88.7 % to 95.4% with the average value of PPD =94.41%. It indicates that finished goods warehouse workers have potential to experience moderate to strong heat stress and discomfort feeling. High air temperature and low air speed contributed significant PMV value comparing to the other factors of relative humidity, metabolism rate, and clothing insulation.

Innovation of air circulation in warehouse building is the best and the cheapest way to maintain air temperature and air speed. According to observation data, the difference of 4°C between indoor and outdoor temperature has been explored by installing 33 exhaust fans with a capacity type of 3610 m^3/h. The solution successfully improved thermal comfort by reducing average value of PMV from 2.55 to 1.60 and PPD value decreased from 94.41 to 56.88%. Reducing heat stress or improving thermal comfort in the warehouse can be optimise by planting more trees near the building, selecting the correct roof materials, ergonomics working system and etc.

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