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Analysis of Thermal Environment in a Hospital Operating Room

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Abstract

This paper presents a computational fluid dynamics (CFD) study for thermal comfort in a hospital operating room. The research aims to analyze indoor thermal comfort using the predicted mean vote (PMV) model which has been presented by ISO7730. The room model includes a patient lying on an operating table with a surgical staff of six members standing around under surgical lights. The airflow is supplied to the room from the ceiling diffuser and exhausted through low-level side walls on both sides. Solutions of distribution of airflow velocity, temperature, relative humidity and so on are presented and discussed. The PMV and PPD are calculated for assessing thermal comfort based on TCM model. The simulation results show that the values of PMV and PPD in some parts of human body are not within the standard acceptable range defined by ISO, but its comfortableness satisfies China national standard GB/T18049 request. It is found that TCM model is a more comprehensive model for thermal comfort analysis.

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Keywords: Clean room; tcm model; thermal comfort; pmv-ppd

1. Introduction

An operating room is one of the most controlled work environments providing a comfortable and healthy environment for both the surgical staff and the patient [1]. Clean operating room is a micro environment where the functional requirement is very high. Architectural technical code for hospital clean operating department (GB50333-2013) is the latest standard published by China, in which control technique of micro-environment in operation

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department is proposed for the requirements of many parameters. In the new version of the specification, giving the designer a relatively loose choice of control parameters on the micro environment of operating room, but presenting a high standard requirement for environmental acceptance criteria. Consequently, it has put forward more high requirements for the designers and the builders. In this paper, through computational fluid dynamics and TCM model to analysis of human thermal comfort in the operating room based on an engineering project. Through the selection and comparison of different calculation conditions, to find a way to meet the environmental requirements, and also take into account the environmental control parameters of human comfort. It can provide a very accurate reference for the construction of the actual environment.

2. Methods

2.1. TCM Model

The TCM model has considered the person of volumetric heat physiological phenomenon (various some human body temperatures, perspiration evaporations and so on) CFD model of heat flux simulation and hot comfortable appraisal. TCM uses one kind of special one-dimensional code TIM (German to condense "Thermo- physiological Occupant Model") with the CFD software joint operation, can the quantification sit in other cars or closed rooms person volumetric heat physiological condition [2].

The TCM model is divided into 14 spots of the human body (e.g. Fig. 1.). Each spot, from the surface to the interior, is divided into "skin - fat -muscle - core" four layers, which considers hot physiological regulations of body temperature among various spots, the evaporation convection heat that through the blood stream accumulates including various spots and central blood carries on the thermal shift assignment, the metabolism hot production and muscle level human body to shiver giving off heat and skin that perspiration causes (with ambient temperature and humidity variable related), the radiation as well as the influence of solar radiation human body and environment, also considers the heat conductions between various human body spots [3]. The TIM procedure code synthesis that the TCM manikin transfers has considered each factor of above regulation of body temperature. Obviously, the TCM model is one kind of more comprehensive hot comfortable anatomic model.

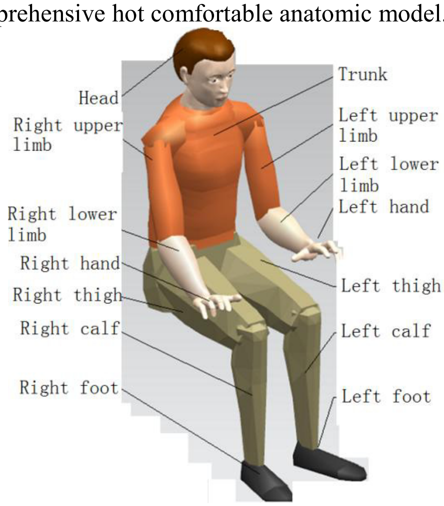

Fig. 1. Stuffed dummy model (picture originates from UG-NX8.0, Siemens, Inc).

2.2. Mathematical Model

During these years, computational fluid dynamics (CFD) technology has progressed and made it possible to analyze complex situations where HVAC systems were simulated [4]. The airflow pattern, velocity and temperature distribution are governed by the conservation laws of mass, momentum and energy. Steady state, three-dimensional, incompressible and turbulent flow of air as a multi-component fluid, which includes dry air and water vapor, is considered. The buoyancy effect is invoked in the momentum equation, k and ε. The Boussinesq approximation hypothesis is used for the buoyant force term. The radiation heat transfer, thermal comfort is integrated in the CFD model, which is called S2S radiation model and TCM model respectively. Physical model of CFD analysis of TCM are listed in Table 1.

Table 1. Physical model of CFD analysis of TCM.

Physical model	Discrete format
Three-dimensional, steady-state, gravity model	
Turbulence model: Realizable k–ε	Second-order upwind
Multi-component model: air, water vapor, non-reactive	Second-order upwind
Density: meet the ideal gas equation of state	
Radiation model: s2s, gray body	
Thermal Comfort: TCM model	
Solution: Separation solution pattern	Second-order upwind

2.3. Numerical Model

An operating room of dimensions 7.0 m×6.0 m×3.0 m is considered as shown in Fig. 2. The air supply diffuser is 2.6m×2.4m which has a vertical laminar airflow supplied from the ceiling, All the air return vents located on low-level side walls have the same size of 0.9m×0.4m. An x, y, z coordinate system is attached to the model with the origin located at the bottom left corner. The 14 spots of stuffed dummy are the mutual independent geometric solids, its dimension scale is consistent with the real human body.

Fig. 2. shows the setup for an operating room including a patient lying on an operating table with a surgical staff of six members(anesthetist, assistant_1, assistant_2, surgeon, instrument nurse, circulating nurse) standing around under a set of surgical lights. Astral lamp, anesthesia machine, instrument table, chair, operating table, apparatus rack and etc are considered in the operating room.

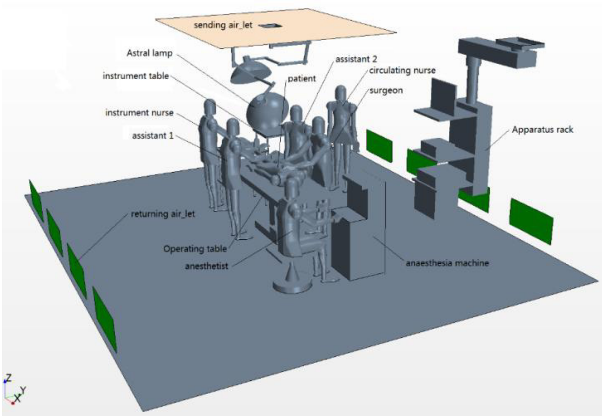

Fig. 2. Computational model of an operating room.

2.4. Discretizaon

The discretization of the computational domain is achieved by means of an unstructured mesh. In the boundary layer next to a non-slip wall, there are high gradients within a small region, so to capture these gradients accurately, it was necessary to have fine mesh spacing normal to the wall. The volume mesh process consisted of several steps, including surface improvement, subsurface generation and then the actual interior volume meshing. Fig.3(a) shows the geometry and the corresponding space discretization, subdividing the operating room into cells. We focus on the thermal condition of the flow field is that human surface and near the surface of body, therefore the mesh of human surface and near the surface of body must take suitable of encryption measures, this is of vital importance to ensure the reliability of the analysis results. Fig.3 (b) shows the space discretization around human body.

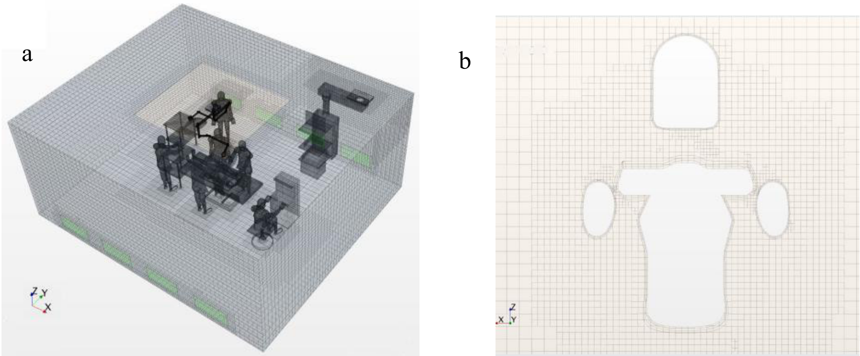

Fig. 3. Grid partition of calculated region.

The grid contains polyhedral elements (Poly), the final mesh being composed of more than 2,860,000 cells, the number of grid points over more than 3.13 million. Polyhedral meshes and the same number of tetrahedral mesh (Tetra), dependence on grid number smaller than tetrahedral, just tetrahedral mesh number one-fourth to guarantee the precision of calculations [5]. A grid dependency analysis was conducted to ensure that the resolution of the mesh was not influencing the results.

2.5. Boundary conditions and thermal performance hypothesis

The indoor design temperature in the operating room is 25℃, design relative humidity is 60%[6]. The adjacent room has the similar air-conditioning system. Heat transfer only considers the external walls. Supply air temperature is 24.5℃, relative humidity is 50%, the air speed is 0.3 m/s, and the supply air volume is calculated about 2.186 kg / s. Numerical values of the boundary conditions and thermal performance hypothesis used for the solution are listed in Table 2.

Table 2. Boundary conditions and thermal performance hypothesis [7, 8, 9]

No.	Boundary name	Boundary conditions	Emissivity	Transmission rate
1	air supply outlet	the mass flow imports, 2.186kg/s, the temperature 24.5℃, the relative humidity 50%	0.02	0.98
2	air return vent	flow split outlet，split ratio=1，total of 8	0.02	0.98
3	surgeon	height 1.75m, clothing thermal resistance 0.22 m2k /w, metabolic rate 2.4met, initial temperature 35℃, no-slip	0.97	0
4	assistant_1	height 1.80m, clothing thermal resistance 0.14 m2k /w, metabolic rate 2.0met, initial temperature 35℃, no-slip	0.97	0
5	assistant_2	height 1.70m, clothing thermal resistance 0.14 m2k /w, metabolic rate 2.0met, initial temperature 35℃, no-slip	0.97	0
6	anesthetist	height 1.68m, clothing thermal resistance 0.14 m2k /w, metabolic rate 1.9met, initial temperature 35℃, no-slip	0.97	0
7	instrument nurse	height 1.65m, clothing thermal resistance 0.14 m2k /w, metabolic rate 2.0met, initial temperature 35℃, no-slip	0.97	0
8	circulating nurse	height 1.60m, clothing thermal resistance 0.14 m2k /w, metabolic rate 1.7met, initial temperature 35℃, no-slip	0.97	0

9	patient	height 1.72m, clothing thermal resistance 0.20 m2k /w, metabolic rate 0.8met, initial temperature 35℃, no-slip	0.97	0
10	interior wall	the coefficient of thermal conductivity 0.76 W/(m·K), convection heat transfer coefficient 23 W/(m2·℃), the external environment temperature 28℃, no-slip	0.60	0
11	Torso wet face	adiabatic, no-slip， moisture diffusion rate 9.72E-6 （kg/m^2s）	0.97	0
12	ceiling	coefficient of thermal conductivity 0.05W/(m·K), convection heat transfer coefficient 15 W/(m2·℃), the external environment temperature 28℃, no-slip	0.60	0
13	floor	the coefficient of thermal conductivity 1.74 W/(m·K), convection heat transfer coefficient 23 W/(m2·℃), the external environment temperature 28℃, no-slip	0.60	0
14	astral lamp	heat dissipation capacity 80W， no-slip	0.80	0
15	astral lamp glass	adiabatic, no-slip	0.80	0
16	astral lamp holder	adiabatic , no-slip	0.80	0
17	anesthesia machine	adiabatic, no-slip	0.80	0
18	anesthesia machine heat face	heat dissipation capacity 100W， no-slip	0.80	0
19	anesthesia machine wet face	Adiabatic, no-slip, moisture diffusion rate 6.94E-6 （kg/m^2s）	0.80	0
20	chair	adiabatic, no-slip	0.80	0
21	instrument table	adiabatic, no-slip	0.80	0
22	instrument table wet face	adiabatic, no-slip， moisture diffusion rate 5.56E-6 （kg/m^2s）	0.80	0
23	operating table	adiabatic, no-slip, 0.9m from the ground	0.80	0
24	apparatus rack	adiabatic, no-slip	0.80	0

Note: metabolic rate 1met = 58.2w/m^2.

3. Results and discussion

3.1. Air velocity distribution

Velocity contour plots are shown in Fig. 4 (a, b) over two different planes. The velocity distributions show downward airflow supply patterns from the ceiling diffusers. The airflow between the ceiling supply plane and the operating table is a unidirectional flow, and the velocity should be between 0.1m/s and 0.4m/s. Reverse flows occurred mostly at the upper part of the operating room, especially in the areas occupied by the medical equipment and personnel. The contour plots over the horizontal planes illustrate the vertical velocity distributions above the operating table.

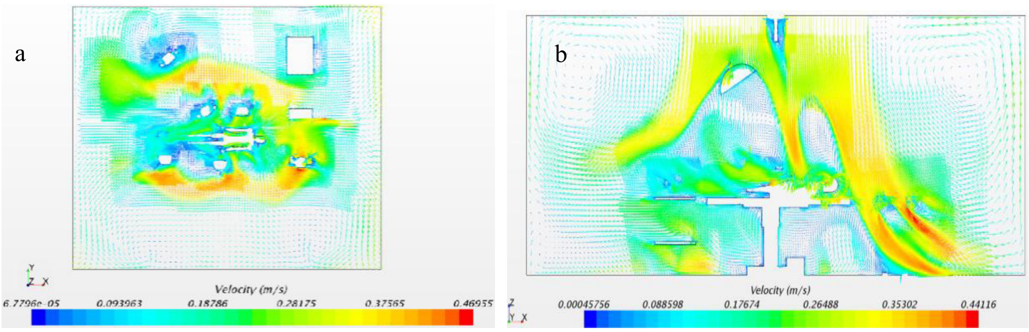

Fig. 4. Velocity contour map: (a) Z=1.02; (b) Y=3.

The air stream passing across the operating table does not come directly from the ceiling diffusers. The operating room corners are the worst positions in terms of old air, and they represent areas of airflow stagnation.

3.2. Temperature distribution

Fig.5 (a,b) shows temperature contour plots over the same planes where previously velocity contour plots are shown. Uniformity in temperature distribution may be maintained for all plots in the occupant region. The temperature variation in the occupied zone is not more than 3℃.

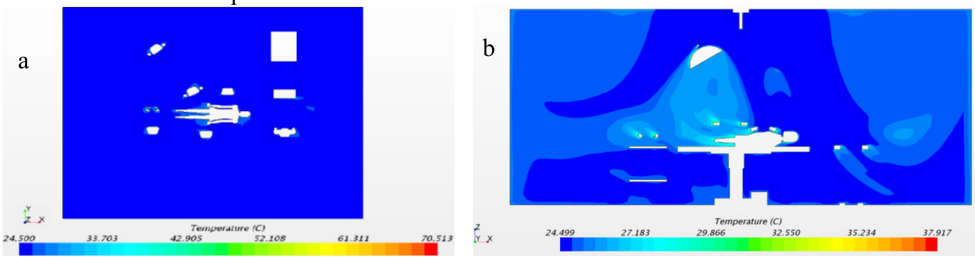

Fig. 5. Temperature contour map: (a) Z=1.02; (b) Y=3.

3.3. Relative humidity(RH(%)) distribution

Fig.6 (a, b) shows relative humidity contour plots over the same planes where previously mean age of air contour plots are shown. Air humidity must be maintained at acceptable levels because it is closely related to the thermal comfort conditions. The recommended levels of indoor relative humidity are 30-60%, according to international regulations and standards[10]. However, in China national standard GB50333-2013, its relative humidity recommendation values are also 30-60%. Fig.6 shows the relative humidity in the operating room is nearly 60%.

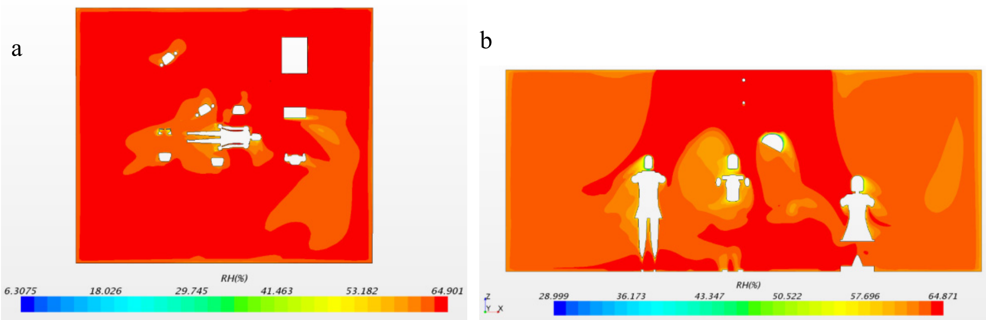

Fig. 6. Relative humidity contour map: (a) Z=1.02; (b) Y=2.5.

3.4. Temperature distribution of human body surface

Fig.7 is human body surface temperature distribution map. Among them, 1 is circulating nurse, 2 is instrument nurse, 3 is assistant_2, 4 is surgeon, 5 is assistant_1, 6 is patient, 7 is anesthetist. As we can see that seven stuffed dummy forehead temperature is quite high. The stuffed dummy patient right upper limb and left upper limb temperature is low. All parts of the surgeon dummy's temperature are low, in addition to the head and hands, because the heat transfer is from the inside to the outside; the larger the surgeon' s clothing thermal resistance, the lower the surface temperature.

3.5. Relative humidity distribution of human body surface

Fig.8 is human body surface relative humidity distribution map (stuffed dummy position with Fig.7). As we can see that seven stuffed dummy forehead and hands relative humidity are relatively low; the difference of relative humidity in other parts is not obvious because of the temperature had little difference. This is consistent with the result of human body surface temperature distribution. According to the related knowledge of engineering thermodynamics, the relative humidity is a function of the temperature; relative humidity is inversely proportional to the temperature, under the same conditions, the higher the temperature, the lower the relative humidity [11].

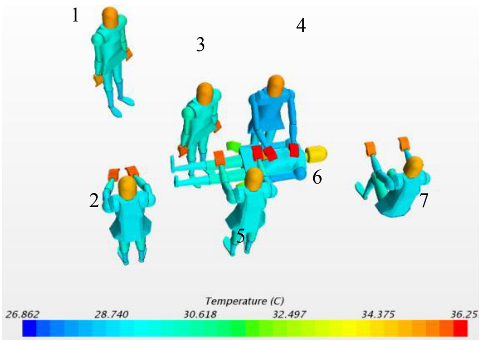

Fig. 7. Temperature distribution of human body surface.

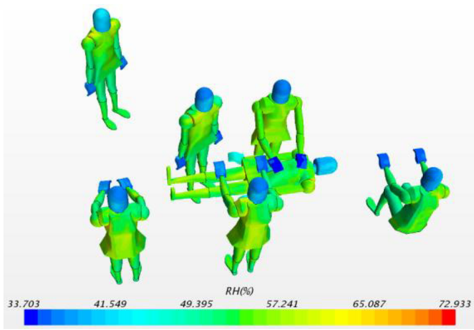

Fig. 8. Relative humidity distribution of human body surface.

3.6. PMV and PPD at different parts of human body

The values of PMV and PPD at different parts of human body are presented in Table 3.

It is seen that nearly all staffs' and the patient's right hand and right foot do not have suitable thermal comfort as their PMV indices do not place within the range [-0.5,+0.5](ISO 7730 pointed out, the acceptable thermal environment for general comfort is recommended as -0.5 < PMV < 0.5 and PPD is smaller than 10% [12]). However, in China national standard GB/T18049, its PMV recommendation values are within the range of [-1.0, +1.0], PPD recommendation value is ≤27% [13]. Obviously this operating room's comfortableness satisfies china national standards request completely. Regarding for the ISO7730 standard, all staffs' right hand and all staffs' and patient's right foot are at slightly warm condition.

Table 3. Values of PMV and PPD calculated at different parts of human body.

human body parts	surgeon		patient		instrument nurse		Circulating nurse		assistant_1		assistant_2		anesthetist	
	PMV	PPD (%)	PMV	PPD (%)	PMV	PPD (%)	PMV	PPD (%)	PMV	PPD (%)	PMV	PPD (%)	PMV	PPD (%)
Head	0.31	7.00	0.31	7.00	0.32	7.13	0.29	6.75	0.32	7.13	0.34	7.40	0.30	6.87
Trunk	0.29	6.75	0.31	7.00	0.32	7.13	0.29	6.75	0.33	7.26	0.33	7.26	0.33	7.26
Left upper limb	0.29	6.75	0.32	7.13	0.28	6.63	0.29	6.75	0.31	7.00	0.31	7.00	0.31	7.00
Right upper limb	0.28	6.63	0.32	7.13	0.28	6.63	0.28	6.63	0.30	6.87	0.29	6.75	0.31	7.00
Left lower limb	0.31	7.00	0.35	7.55	0.32	7.13	0.31	7.00	0.33	7.26	0.33	7.26	0.33	7.26
Right lower limb	0.30	6.87	0.35	7.55	0.33	7.26	0.31	7.00	0.33	7.26	0.32	7.13	0.34	7.40
Left hand	0.46	9.42	0.34	7.40	0.47	9.61	0.43	8.86	0.47	9.61	0.45	9.23	0.43	8.86
Right hand	0.53	10.88	0.42	8.68	0.54	11.10	0.52	10.66	0.53	10.88	0.53	10.88	0.51	10.44
Left thigh	0.25	6.30	0.26	6.40	0.29	6.75	0.28	6.63	0.28	6.63	0.30	6.87	0.25	6.30
Right thigh	0.29	6.75	0.31	7.00	0.35	7.55	0.37	7.85	0.36	7.70	0.34	7.40	0.31	7.00
Left calf	0.25	6.30	0.25	6.30	0.28	6.63	0.30	6.87	0.27	6.51	0.31	7.00	0.27	6.51
Right calf	0.29	6.75	0.30	6.87	0.33	7.26	0.37	7.85	0.35	7.55	0.36	7.70	0.32	7.13
Left foot	0.24	6.20	0.28	6.63	0.27	6.51	0.30	6.87	0.28	6.63	0.30	6.87	0.27	6.51

Right foot	0.61	12.80	0.58	12.05	0.60	12.55	0.63	13.33	0.61	12.80	0.62	13.06	0.60	12.55

4. Conclusions

The use of TCM model and coupled CFD analysis on thermal comfort of human body, contribute to the consideration with the combined effect on internal factors and external factors. It is found that TCM model can give thermal comfort index of PMV (or PPD) value which is considering the above factors, and can point out that all parts of the human body are in a state of thermal comfort. It is found that TCM model is a more comprehensive model for thermal comfort analysis.

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