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Clarifying Optimum Setting Temperatures and Airflow Positions for Personal Air Conditioning System on Flight

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Abstract:

In recent years, the demand for air travel has increased and many people have traveled by plane. Most passengers, however, feel stressed due to the limited cabin space. In order to make these passengers more comfortable, a personal air-conditioning system for the entire chair is needed. This is because the human body experiences discomfort from localized heating or cooling, and thus, it is necessary to provide appropriate airflow to each part of the body. In this paper, a personal air-conditioning system, which consists of six vertically installed air-conditioning vents, will be proposed. To clarify the setting temperature of each vent, the airflow around the passenger and the operative temperature of each part of the body is investigated using fluid simulation. In the simulation, the ideal temperature for each part of the body is defined and compared with the operative temperature to verify how close both temperatures are, resulting in determining the ideal setting temperature. The simulation result shows, that most parts of the body reach their ideal temperatures. In addition, the optimum setting temperature and position of each air-conditioning vent, which contribute to maintaining the thermal comfort of the human body on the plane, is clarified.

Keywords: Air-conditioning system, Airflow, Airplane, Ansys, CFD, Operative temperature, Temperature.

Introduction:

The demand for the airline industry has increased regardless of age with globalization. Accordingly, the number of tourists has been increasing[1]. However, the limited space of an airplane could be factors of various kinds of stress[2-4]. One of these factors is the temperature inside the cabin, which is kept at around 24 °C all year round. Therefore, the passenger tends to feel cold in the winter season or when wearing light clothes for a long time. There is a small blower above each seat in the cabin. However, it is not temperature-controlled and is only useful when passengers want to feel cooler. Therefore, passengers have no choice but to use a jacket or blanket to protect themselves when they feel cold. However, it is not enough for customers who are sensitive to cold or have a cold constitution. Especially, reducing blood flow to the legs induces the development of the economy-class syndrome and swollenness. Therefore, it is necessary to introduce a personal air-conditioning system that can adjust the temperature around the feet and the others based on the sense of each passenger.

Although the personal air-conditioning systems to improve the comfort of individuals have been investigated in some previous works[5-6], but most of them have been carried out inside the building, and less on airplanes. Few studies have been conducted on personal air distribution systems considering comfort and health, but not the sense of individuals. Regarding that air distribution system, it aimed to supply a lower temperature around the face for breathing[7-10]. However, it could cause drafts and compromise comfort. To prevent draft generation and maintain comfort, it is desirable to propose a personal air-conditioning system that can control suitable temperature.

In this study, the investigated personal air-conditioning system signifies a whole chair system such as a cool chair, which provides optimum airflow to each part of the body. The appropriate location and temperature of the personal air-conditioning system are clarified to provide appropriate airflow to each part of the body in this paper. Toward the realization of such a personal air-conditioning system, an ideal temperature of each part of the body is defined, and the methodology which makes the temperature of each part reach the ideal temperature is discussed. This research is expected to clarify the air outlet position that affects each part of the human body in a seated posture, and to clarify the setting temperature of the personal air-conditioning system which could be an indicator showing that the thermal comfort is maintained.

The rest of the paper is organized as follows: In Section 2, the related work is stated. Section 3 mentions the proposed methods and analytical way. The verification of the setting temperature and air conditioning position for the optimum personal air-conditioning is shown in Section 4. Discussions based on the verification results are described in Section 5. Finally, Section 6 concludes this paper.

Related works:

The sensation of warmth and cold varies among people, thus, “comfortable feeling” might be different even in the same environment. ASHRA classifies an environment as "comfortable" if more than 80% of the population can states they feel "satisfied" with it[11]. Even at a recommended temperature, some people feel uncomfortable depending on the difference in constitution. In a non-uniform environment, Pellerin et al. showed that even when the average skin temperature is in the thermally comfortable range, a comfortable sensation cannot be achieved if a localized thermal discomfort occurs[12]. In other words, in order to provide a comfortable and pleasant environment for all people, it is necessary to provide an environment that suits the physical constitution of each individual. As the result, air-conditioning control for each individual and each part of the body is considered essential.

In the human sitting state, several studies have verified the effectiveness of a personal air-conditioning system placed in front of or behind the human body[5-6]. However, since comfort was evaluated by calculating PMV (Predicted Mean Vote) and other indices, the comfort of each individual was not considered. Furthermore, those results could not be valid in all environments because airflow may lead to turbulence depending on the space and distance. Therefore, it is necessary to consider the personal air-conditioning system in the special environment of airplane. For a personal air-conditioning system on airplane, personal air distribution systems have been studied[7-10]. However, they focus on comfortable breathing, not on the individual thermal sensation.

In this study, in order to provide appropriate airflow to each part of the body in the special environment of an airplane, an air conditioning system such as a cool chair with the entire surface of the seat is proposed. Its effectiveness and functionality are verified by fluid simulation.

Proposed methods:

In this section, the proposed personal air-conditioning system on flight will be presented. To improve the thermal comfort of passengers during the flight, the proposed system is required to provide appropriate airflow that suits individual passenger. The personal air-conditioning system should be embedded on the entire surface of the seat so that turbulence is less generated, while the airflow can be directly blown to each part of the body. By appropriately controlling the airflow, the ideal temperature of each part of the body will be achieved, resulting in expected “comfortable feeling”. Therefore, in this section, the ideal temperature distribution over human body will be firstly investigated. Then, the simulation software, proposed analysis model and the calculation method of operative temperature will be presented, respectively.

Ideal temperature distribution

In this paper, the target ideal temperature is introduced based on the study of Hori et al.[13]. Accordingly, the optimum temperature was defined as the one by operative temperature, feeling neither hot nor cold at any part of the body. Table 1 shows the optimum operative temperatures, in other words, the ideal temperature for each body part. Matsuo et al. showed that keeping head cool and feet warm improved comfort[14]. This table also shows that head cold and feet heat. Hori et al. reported that even when whole-body warm and cold sensations are neutral, there is a local load on the human body, which may be uncomfortable in localized parts. We assume that comfort is maintained when each part of the body is set to a suitable temperature as shown in this table.

Table 1. Ideal temperature distribution for each body part.

Body parts	Head	Arm	Forearm	Back	Chest	Hip	Thigh	Legs	Foot
Optimum operative temperature[℃]	22.3	23.7	23.3	23.6	22.9	23.3	25.3	26.3	26.6

Analysis settings

Recently, a large number of studies have used simulations to verify[15]. In this paper, the verification is conducted with fluid analysis software, Ansys Student. This is an analysis tool based on finite elements method[16]. Although Ansys Student has several limitations as it is designed for students, it is sufficient for our purpose, which is to reveal temperature changes and wind flow in a simple aircraft. Table 2 shows the analysis conditions and settings, based on the one in[7]. Meanwhile, table 3 and table 4 provide physical properties of each material and skin temperature which are extracted and adopted from the works by Yokoyama et al. and Tanaka et al.[17- 18]. The walls, outlets and inlets are set uniformly at 25°C because it is assumed that the skin temperature of the human body is regarded as 25°C.

Table 2. Analysis conditions and settings.

Setting item	Setting details
Analysis conditions	Transient analysis / Incompressible flow
Material (substance name)	Air / Aluminum / Skin
Target flow	Standard k-εturbulence model
Analysis methods (calculation algorithms)	SIMPLE Algorithm
Advection equation	First order upwind scheme

Table 3. Physical properties of materials.

Material	Density	Specific heat	Heat transfer coefficient	Viscosity
	kg/m^3	j/kg*k	w/m*k	kg/m*s
Air	1.225	1006.43	0.0242	1.79E-05
Aluminum	2719	871	202.4	
Skin	1200	3390	1.58	

Table 4. Skin temperature of each body part.

Body parts	Head	Arm	Forearm	Back & chest	Thigh	Legs	Foot
Temperature [℃]	33.6	30.95	30.4	32.4	30.7	30.2	27.25

Analysis model

In creating the model, a part of the cabin was simulated due to the limitation of the software. The size of the model to be analyzed was a hexahedron box, 2.3m height, 2m depth, and 1m width, in which two chairs were placed in a row and a human body model was placed. Fig. 1 shows the model. This unit is meter. To generate ordinary airflow, the air outlet is placed on the upper left side, and the inlet is placed on the lower right side. The dimensions of the human body were cited from the database of human body dimensions published by the Center for the Study of Population Intelligence, which are the average values of adult males in the sitting position[19]. The distance between the front and back seats was based on the actual economy class seat distance, and the chair dimensions were based on the ones of an office chair.

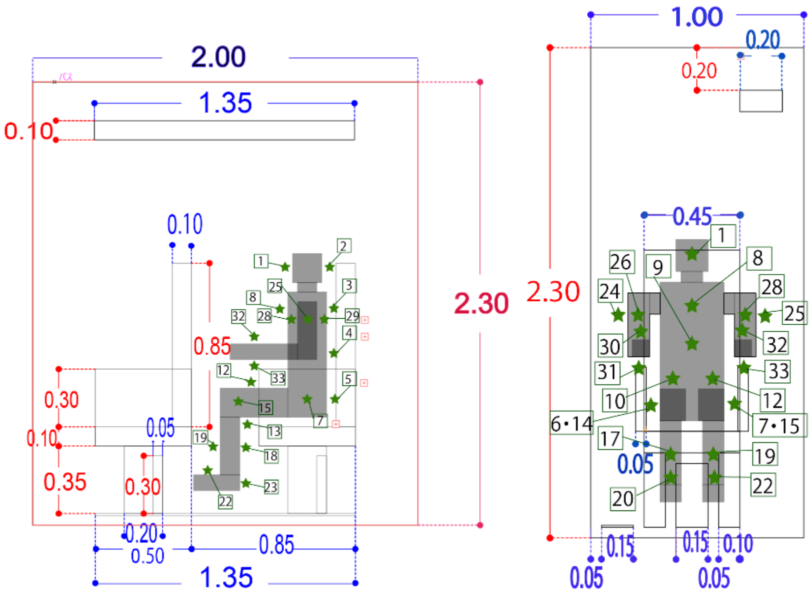


Figure 1. Analysis model dimensions in X-axis(right) and Y-axis(left).

Table 5. The number of measuring points in each part of the body.

Body parts	No. measurement point
Head	1~2
Back	3~4
Hip	5~7
Chest	8~9
Thigh	10~15
Legs	16~19
Foot	20~23
Arm	24~29
Forearm	30~33

Method of calculation of operative temperature

In this paper, the human body temperature is measured through 33 measurement points across human body. Fig. 1 shows 33 measurement points in green stars. Table 5 shows the number of measuring points in each part of the body. These measurement points are 3 cm away from the skin to guarantee the convection temperature near the skin. These measuring points were positioned to encompass the entire surface of the body.

The target ideal temperature shown in Table 1 is the optimum operative temperature, which needs to be calculated. In general, the operative temperature is one of the indicators to evaluate the thermal environment for the human body, and the convective and radiative heat transfer coefficients must be factored in. However, since this research focuses on the change in airflow, the calculation method of the operative temperature is the average of the air temperature and the temperature at each measurement point. Equation 1 shows the calculation formula, where $\boldsymbol{t_0}$ stands for operative temperature; $\boldsymbol{t_a}$ is atmospheric temperature; and $\boldsymbol{t_r}$ is temperature around the human body.

$$\boldsymbol{t_0} = \frac{\boldsymbol{t_a} + \boldsymbol{t_r}}{\boldsymbol{2}} \quad \ldots (\boldsymbol{1})$$

Verification of setting temperature and air-conditioning position:

Overview

In this section, the ideal temperature for each part of the body will be investigated in order to clarify how to provide appropriate airflow. Then, the setting temperature and blowing position of the personal air- conditioning system will be determined, which will give the ideal temperature for each part of the body. To do this, the location of the air-conditioning where the airflow spreads out around the human body must be examined. The proposed personal air-conditioning system is vertically divided into several parts and each part can blow air with a different setting temperature. Varying the setting temperature in each part, an appropriate set of temperatures will be determined to meet the ideal temperature for each part of the body. The setting temperature range is determined by considering the difference between the operative temperature of the human body and the ideal temperature in the normal cabin environment. Note that this difference will be discussed in next Subsection.

Simulation setting

In the simulation, the proposed location of the personal air-conditioning system is set in a seat such as a cool chair so that the airflow can be directed to each part of the body. The proposed personal air-conditioning system acts to the passenger from three directions, which are the back of the front seat, the inside of the elbow rest and the surface of the seat. It is assumed that the airflow generated by the three directions shown in Fig. 2 is appropriate to evenly spread over each part of the body. To generate such airflow, the outlet and the inlet are set up as shown in Fig 3. The outlet is shown in red and the inlet is shown in blue. Since a leg of the front seat is not large enough for inlet, another inlet is added in the middle of the legs.

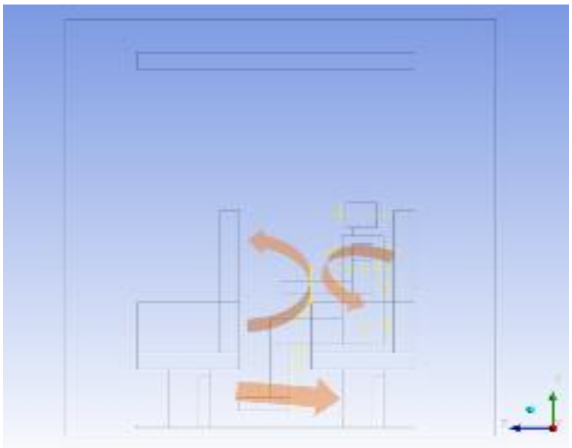
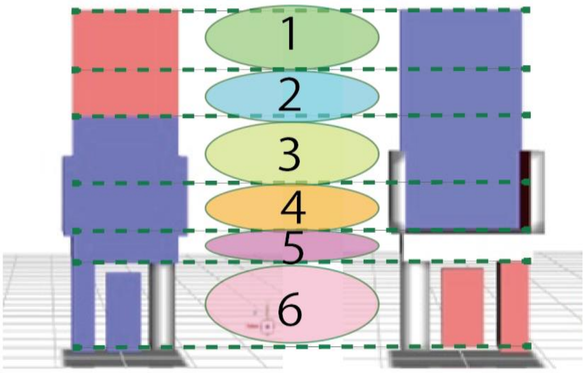


Figure 2. Predicted airflow.



ront seat **Seat**

Figure 3. Outlets and inlet for personal air-conditioning system and Blowing position is divided into six air-conditioning.

In order to provide a different airflow with a different temperature to each part of the body, the blowing position is divided into six sections by height as shown in Fig. 3. Each section of the blowing position is called air-conditioning with a different number, which will be referred to as the air-conditioning number. Air-conditioning number 4 and 5 have a front and behind blowing position, so different temperatures can be set for the front and behind.

Table 6. Air blowing temperature [°C].

Duration time / No. of air-conditioning	1	2	3	4	5	6
0~119sec	20	21	22	23	31	32
120~179sec	18	19	20	21	29	30
180~239sec	16	17	18	19	27	28
240~300sec	14	15	16	17	25	26

Table 6 shows the setting temperature for each air-conditioning varied by duration time. Each setting temperature is determined from the head to the feet so that lower temperatures for the upper body and higher temperatures for the lower body can be applied. Since the temperature tends to fluctuate at the beginning of analysis, the duration time for the first setting temperature is set to 120 seconds, and then, the temperature is varied by 60 seconds. The analysis is performed for a total of 300 seconds. As for the setting air velocity, it is set to 0.2 m/s for all air-conditionings, which does not cause discomfort referring to the study by Griefahn et al.[20]. For the ordinary airflow, at the inlet above the passengers, the temperature is set to 25°C and the air velocity is set to 0.2 m/s, referring to the air-conditioning in the cabin.

Simulation Result

In order to clarify how different the operative temperature of the human body is from the ideal temperature under ordinary cabin conditions, an analysis was performed for 180 seconds with ordinary airflow. The transition of the operative temperature in each part is shown in Fig. 4. It shows that the airflow is unstable and the operative temperature around the human body fluctuates at the beginning, but after around 60 seconds, it becomes stable. The value of the stable operative temperature in each part was extracted, averaged and compared to the ideal temperature. Table 7 presents the difference between the average value of stable operative temperature and the ideal temperature in each part. It reveals that cooler air is needed for the upper body, and conversely, warmer air is needed for the lower body.

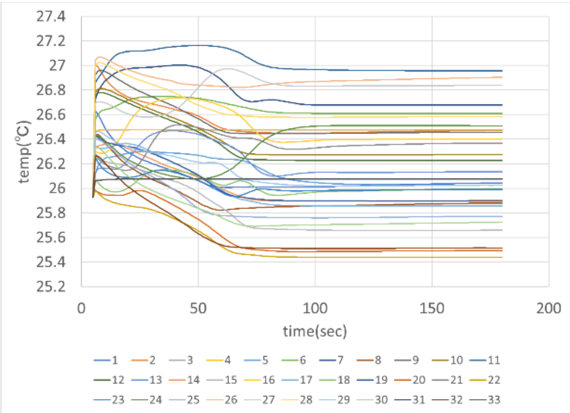


Figure 4. Operative temperature at 33 parts.

Table 7. Difference between operative temperature and ideal temperature in each part.

Body parts	Operative Temperature - Ideal Temperature[℃]
Head	3.96
Back	2.88
Hip	3.14
Chest	3.27
Thigh	0.89
Legs	-0.26
Foot	-0.78
Arm	2.74
Forearm	2.55

Considering the results in Table 7, the temperature setting of each air-conditioning was varied as shown in Table 6, and the operative temperature in each part (33 parts) was measured. To simplify the comparison, the temperatures of the 33 parts measured were divided into 9 parts, and the average values were calculated for each 9 parts. The average temperature in each part was converted to the operative temperature and compared to the ideal temperature. The results are shown in Fig. 5.

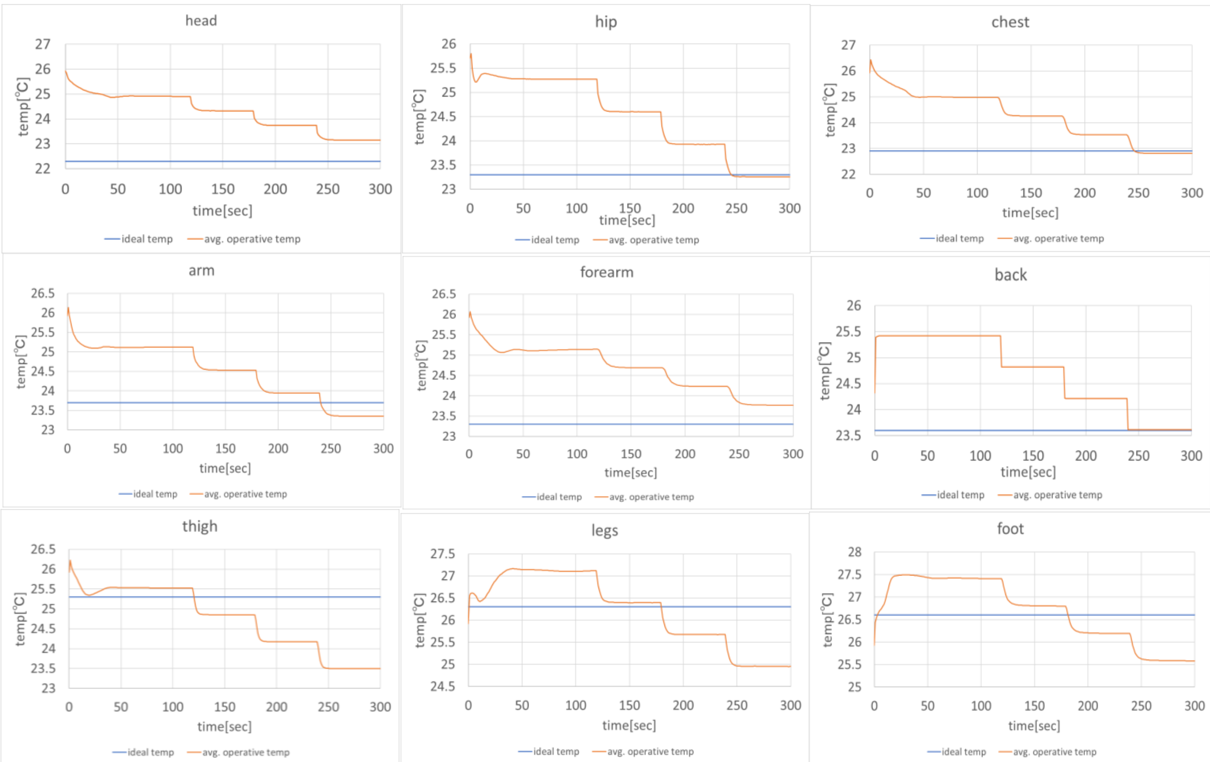


Figure 5. The ideal temperature and the average of operative temperature at each body part.

The variation of the overall operative temperature shows that it is affected by the setting temperature, and it is confirmed that the operative temperature decreases as the setting temperature decreases. Moreover, the operative temperature except for head and forearm reached the ideal temperature. In arms, thighs and feet, the operative temperature reached the ideal temperature at the time of the setting temperature change. However, since these graphs are not enough to identify which part of the body was being affected by which airflow from which air-conditioning. Therefore, the airflow from each air-conditioning should be investigated.

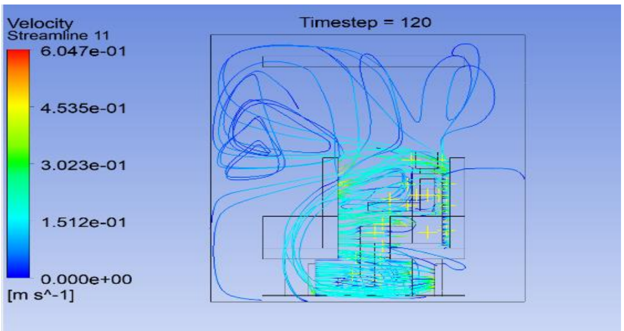
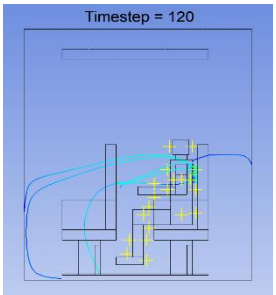
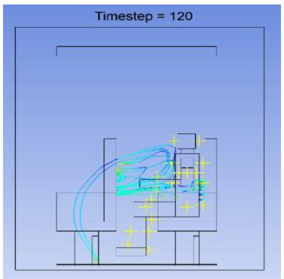


Figure 6. Airflow of the proposed personal air-conditioning system.

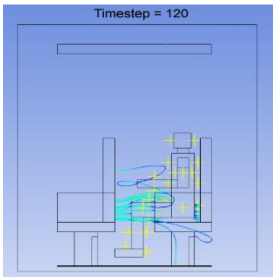
A/C Number 1



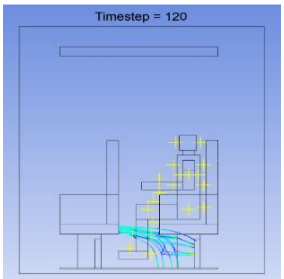
A/C Number 2



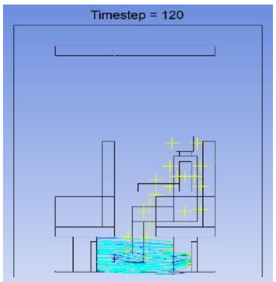
A/C Number 3



A/C Number 4



A/C Number 5



A/C Number 6

Figure 7. Airflow from each air-conditioning (A/C is air-conditioning).

The overall airflow generated by the proposed personal air-conditioning system is shown in Fig. 6. From this figure, it can be seen that the airflow from the outlets covers the entire body as expected. The airflow from each of these six air-conditionings is shown in Fig. 7 (1) – (6) to confirm which area is being affected. It can be seen that each air-conditioning affects a different part of the body. It can also be seen that in air-conditioning numbers 2, 3 and 4, these airflows are distributed to multiple parts at each blowing position. In air-conditioning number 2, the airflow is distributed to the upper back and arms; in air-conditioning number 3, the airflow is distributed to the chest, stomach, forearms, and middle of the back; and in air-conditioning number 4, the airflow is distributed to the thighs and hips.

Discussion:

From the results in the previous section, it has been confirmed that most parts of the body reach their ideal temperatures and the affected part of the body depends on the blowing position. In this section, based on the relation between the airflow and the operative temperature in each part, the setting temperature of each air-conditioning with which all the body parts reach the ideal temperatures will be discussed.

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Table 8. Optimum setting temperature for personal air-conditioning system and the body parts affected by each air-conditioning. (F: front seat, S: seat)

No. of air-conditioning	1		2			3			4		5		6	
Location of the inlet	F	S	F	S		F		S	F	S	F	S	F	S
Setting temperature		14>		15	16	16	16>	16	22	17	29		29	
Affect part		Head		Upper back	Arm	Chest	Forearm	Middle back	Thigh	Hip	Legs		Foot	

At first, as for the head, it is affected by the airflow from air-conditioning number 1, and the operative temperature of the head did not reach the ideal temperature. Therefore, the setting temperature of air-conditioning number 1 must be lower than 14°C for the operative temperature to reach the ideal temperature. As for the arm, it is affected by the airflow from air-conditioning number 2. Since the operative temperature becomes lower than the ideal temperature as soon as the setting temperature of air-conditioning number 2 is changed to 15°C at the duration time of 240 seconds, it is expected that the setting temperature of air-conditioning number 2 will be 16°C because when the setting temperature is 17°C, the operative temperature does not reach the ideal temperature. For the back, it is mainly affected by the air from the behind and the operative temperature reaches the ideal temperature at the duration time of 240 seconds. Therefore, it is expected that the operative temperature of the entire back will reach the ideal temperature when the setting temperatures of air-conditioning number 2 and the one of the air-conditioning number 3 in the seat (not in the front seat) are 15°C and 16°C, respectively. The chest receive airflow from air-conditioning number 3 in the front seat and the operative temperature reach the ideal temperature at the duration time of 240 seconds. Thus, it is expected that the setting temperature of air-conditioning number 3 in the front seat is 16°C. In the forearm, the airflow from air-conditioning number 3 in the front seat is dominant. However, the operative temperature does not reach the ideal temperature, and thus, the setting temperature of air-conditioning number 3 in the front seat should be lower than 16°C. The hip area is exposed to airflow from air-conditioning number 4 in the seat (not in the front seat) and the operative temperature reaches the ideal temperature at the duration time of 240, which means that the setting temperature of air-conditioning number 4 in the seat is 17°C. In the thighs, the operative temperature reaches the ideal temperature at the time duration of 120 seconds, influenced by the airflow from air-conditioning number 4 in the front seat. Hence, the setting temperature of air-conditioning number 4 in the front seat is approximately 22°C. The legs received airflow from air-conditioning number 5 and the operative temperature reaches the ideal temperature at the time duration of 120 seconds. Hence, the setting temperature of air-conditioning number 5 is 29°C. Lastly, the feet are affected by the airflow of air-conditioning number 6 and the operative temperature reaches the ideal temperature at the time duration of 180 seconds, which means that the setting temperature of air-conditioning number 6 is 29°C.

All these discussions are summarized in Table 8. If each air-conditioning's setting temperature is set to the value in the table, the temperatures of all parts of the body reach the ideal temperatures, which means that a comfortable environment for the human body can be provided. However, if the airflow from a single outlet affects multiple parts of the body, it is difficult for the temperatures of all parts to reach the ideal temperatures at the same time. For example, the setting temperature of air-conditioning number 3 is different for the forearm and chest. However, by considering the changes over time, it would be possible to keep each part of the body comfortable. More concretely, it is possible to maintain comfort by alternately providing airflow with suitable temperature settings for each part at certain intervals. Consequently, Table 8 shows the optimum personal air-conditioning setting temperatures with which the thermal comfort of the human body is maintained. Furthermore, from this table, it is obvious which part of the body is affected by which outlet airflow.

Conclusion and future tasks:

In this paper, the optimum air-conditioning position and the setting temperature of each air-conditioning were focused on using a simplified model created in CFD simulation, which aimed to improve the comfort of passengers on airplane. In the verification experiment, as shown in Table 8, the appropriate temperature setting for each part of the human body was clarified by comparing the operative temperature of each part in the human body and the ideal temperature of the reference[13].

Moreover, the air outlets that affect each part was clarified. Thereby, the optimum setting temperature and position of the personal air conditioning system for maintaining the thermal comfort of the human body were able to be specified.

It is clarified that the difficulty was revealed that all the parts in the human body achieve the ideal temperature simultaneously. However, as a future task, if considering the temporal changes in temperature of inlet, we believe that the ideal temperature distribution could be achieved. Moreover, it was assumed that to reaching the ideal temperature distribution referred to the previous studies is regarded as "comfortable" in this paper. However, it is desired to propose a method by which the ideal temperature can be adapted to individuals.

Authors' declaration:

- Conflicts of Interest: None.
- We hereby confirm that all the Figures and Tables in the manuscript are mine ours. Besides, the Figures and images, which are not mine ours, have been given the permission for re-publication attached with the manuscript.
- The author has signed an animal welfare statement.
- Ethical Clearance: The project was approved by the local ethical committee in Shibaura Institute of Technology.

Author's contributions:

Y.M. conceived of the presented idea, developed the theory and performed the computations, and verified the analytical methods. K.M., P.H.T. and E.K. supervised the findings of this work. All authors discussed the results and contributed to the final manuscript.

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توضيح إعدادات درجة الحرارة المثلى ومواقع تدفق الهواء لأنظمة تكييف الهواء الشخصية على الرحلات الجوية

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الخلاصة:
في السنوات الأخيرة ، ازداد الطلب على السفر الجوي وسافر كثير من الناس بالطائرة .ومع ذلك ، يشعر معظم الركاب بالتوتر بسبب مساحة المقصورة المحدودة .من أجل جعل هؤلاء الركاب أكثر راحة ، هناك حاجة إلى نظام تكييف هواء شخصي للكرسي بأكمله .هذا لأن جسم الإنسان يعاني من عدم الراحة من التسخين أو التبريد الموضعي ، وبالتالي ، من الضروري توفير تدفق هواء مناسب لكل جزء من أجزاء الجسم .في هذا البحث ، سيتم اقتراح نظام تكييف هواء شخصي ، يتكون من ستة فتحات لتكييف الهواء مثبتة رأسياً .لتوضيح إعداد درجة الحرارة لكل فتحة ، يتم فحص تدفق الهواء حول الراكب ودرجة حرارة التشغيل لكل جزء من أجزاء الجسم باستخدام محاكاة السوائل .في المحاكاة ، يتم تحديد درجة الحرارة المثالية لكل جزء من أجزاء الجسم ومقارنتها بدرجة حرارة التشغيل للتحقق من مدى قرب كلتا درجتي الحرارة ، مما يؤدي إلى تحديد الإعداد المثالي لدرجة الحرارة .تظهر نتيجة المحاكاة أن معظم أجزاء الجسم تصل إلى درجة حرارتها المثالية . بالإضافة إلى ذلك ، تم توضيح الإعداد الأمثل لدرجة الحرارة وموضع كل فتحة مكيف هواء ، مما يساهم في الحفاظ على الراحة الحرارية لجسم الإنسان على متن الطائرة.

الكلمات المفتاحية :نظام تكييف الهواء ، تدفق الهواء ، الطائرة ، جود، أنسيس ، درجة حرارة التشغيل ، درجة الحرارة.