536.242:532.582

Paper No. 218-14

Heat Transfer on Cylinder Covered with Close-fitting Fabrics

(Part II, Heat Transfer on the Stagnation Point)*

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The objective of investigation is to get a clear idea of the nature of wind penetration effects in clothing. The preceding study of wind penetration through fabric is extended, in this paper, to determine the heat transfer of fabric system. With the aid of heat transfer equation of porous media, the thermal insulation value of fabric layer can be described as a function of such arguments as α^* , some pertinent properties of fabric and wind velocity, where α^* is the characteristic number of contact layer referring to the manner of contact between fabric and cylinder. Quantitative agreement between the theory and experimental data is considerably good. Then it is seen that the dynamic pressure of wind sets up penetration, and thereby augments heat transfer process. The insulation value decreases with an increasing wind velocity and the behaviour of the decreasing depends largely on α^* . Therefore α^* is an essential factor for assessing the value of a sample fabric in wind.

Key Words: Convective Heat Transfer, Covering with Fabrics, Clothing Function, Wind Penetration

1. Introduction

Necessary Clo value of clothing can be attained by adopting proper materials. The sorts of materials are usually chosen through the heat transfer test established by the authoritative organization such as ASTM and British Standards Institute. However, real clothing systems are often not the same as treated in the test method, and heat may occasionally flow through an unexpected path.

In the wind, penetration into fabrics has an effect on thermal insulation. It is generally recognized that the insulation value depends on permeability, thermal conductivity, and thickness of fabric, and the manner of contact between fabric and body. But there is no common knowledge on the functions of these factors. Especially the last one remains quite unknown. Then experiments cannot yet determine the absolute value of materials. It is not in the interest of scientific progress that this state of affairs should be allowed to continue.

We study theoretically, in this paper, the heat transfer from a cylinder which is covered closely with a layer of fabric; being the simplest model of clothing system,

the cylinder is occasionally used in experimental studies to estimate the insulation value in wind.

There is no air layer between a close-fitting fabric and a heated cylinder, but it was found in the preceding paper that various degrees of fitting are possible and it was assumed that a contact layer is a highly permeable path of penetration. The degree of fitting was defined by the characteristic number of contact layer. Using the characteristic number, pressure distribution in the fabric layer could be described clearly under any wind velocities.

The penetration rate and heat transfer coefficient are to be calculated theoretically with the aid of this number. This paper shows the heat transfer coefficient obtained by an analysis on the stagnation point, which is usually the coldest spot.

Nomenclature

- c_a : specific heat of air at constant pressure
- C_n^* : Fourier coefficient of outer pressure distribution
- D : diameter of heated cylinder
- h : overall heat transfer coefficient on covered cylinder
- h_A : heat transfer coefficient at external air flow
- I : overall thermal resistance
- I_A : thermal resistance at external air flow
- I_F : thermal resistance of fabric layer
- I_{F0} : thermal resistance of fabric layer without wind penetration
- k : permeability of fabric layer, $k^* = k/D^2$
- N_u : Nusselt number on covered cylinder, $= hD/\lambda_a$
- P : pressure distribution, $P^* = P/(\rho_a U^2/2)$

* Received 17th November, 1980.

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- $P_{r*} = P_r \cdot (\lambda_a / \lambda_m)$, P_r is Prandtl Number of air.
 q_w : heat flux density at heated cylinder surface
 r : radius vector, $r^* = r/D$
 Re : Reynolds number, $= DU/\nu$
 U : wind velocity
 v : penetration flow rate, $v^* = v/v_0$
 v_0 : characteristic penetration flow rate
 x, y : rectangular coordinates, $x^* = x/D, y^* = y/D$
 α^* : characteristic number of contact layer
 δ : thickness of fabric layer, $\delta^* = \delta/D$
 ϵ : index number of thermal resistance of fabric layer, $= I_r / I_{r0}$
 θ : angle from stagnation point
 λ_a : thermal conductivity of air
 λ_m : thermal conductivity of fabric layer
 μ : air viscosity
 ν : kinematic viscosity of air
 ρ_a : air density

2. Theory

2.1 Penetration flow

Pressure in the fabric is (1)

$$P^*(r^*, \theta) = \sum_{n=0}^{\infty} \frac{C_n^* \{ (1+2na^*)(2r^*)^n + (1-2na^*)(2r^*)^{-n} \} \cos n\theta}{(1+2na^*)(1+2\delta^*)^n + (1-2na^*)(1+2\delta^*)^{-n}}, \quad (1)$$

where δ^* is the thickness of fabric layer, α^* is the characteristic number of contact layer, and C_n^* are the Fourier coefficients for the pressure distribution around the outer circumference of fabric layer. Coordinates r and θ are shown in Fig.1.

Fig.1 Heated cylinder covered with fabric layer

Differentiating the pressure distribution $P^*(r^*, \theta)$ according to the following law of Darcy, penetration flow $\vec{v}$ is obtained;

$$\vec{v} = -\frac{k}{\mu} \text{grad } P, \quad (2)$$

where k is the permeability of the fabric layer, μ is the viscosity of air. Introducing a characteristic flow rate of penetration v_0 as follows

$$v_0 = kU^2 / (2\nu D), \quad (3)$$

$\vec{v}$ of Eq.(2) takes a dimensionless form as follows

$$\vec{v}^* = -\left(\frac{\partial P^*}{\partial r^*}, \frac{1}{r^*} \frac{\partial P^*}{\partial \theta} \right). \quad (4)$$

The right hand side assumes the following explicit form when Eq.(1) is substituted for P^* ;

$$\frac{\partial P^*}{\partial r^*} = \sum_{n=1}^{\infty} \frac{2nC_n^* \{ (1+2na^*)(2r^*)^{n-1} - (1-2na^*)(2r^*)^{-n-1} \} \cos n\theta}{(1+2na^*)(1+2\delta^*)^n + (1-2na^*)(1+2\delta^*)^{-n}},$$

$$\frac{1}{r^*} \frac{\partial P^*}{\partial \theta} = -\sum_{n=1}^{\infty} \frac{2nC_n^* \{ (1+2na^*)(2r^*)^{n-1} + (1-2na^*)(2r^*)^{-n-1} \} \sin n\theta}{(1+2na^*)(1+2\delta^*)^n + (1-2na^*)(1+2\delta^*)^{-n}}. \quad (5.a) \quad (5.b)$$

The wind penetration is described explicitly here.

For further development of the theory, we introduce an approximation for the stagnation point. The cylindrical coordinates are related to the rectangular coordinates (x^*, y^*) as follows

$$r^* = \sqrt{x^{*2} + (0.5 + y^*)^2}, \quad (6.a)$$

$$\sin \theta = x^* / \sqrt{x^{*2} + (0.5 + y^*)^2}, \quad (6.b)$$

$$\cos \theta = (0.5 + y^*) / \sqrt{x^{*2} + (0.5 + y^*)^2}. \quad (6.c)$$

They are schematically shown in Fig.1. Then the relations of (5.a) and (5.b) become a function of (x^*, y^*) . Their Taylor expansions with higher order terms than the first order of x^* and/or y^* cut off are enough to describe the state near the stagnation point. Approximate forms are

$$\frac{\partial P^*}{\partial r^*} = \sum_{n=1}^{\infty} \frac{8n^2 C_n^* (a^* - 2a^* y^* + y^{*2})}{(1+2na^*)(1+2\delta^*)^n + (1-2na^*)(1+2\delta^*)^{-n}}, \quad (7.a)$$

$$\frac{\partial P^*}{r^* \partial \theta} = -\sum_{n=1}^{\infty} \frac{8n^2 C_n^* x^*}{(1+2na^*)(1+2\delta^*)^n + (1-2na^*)(1+2\delta^*)^{-n}}. \quad (7.b)$$

The wind penetration towards the stagnation point is, then,

$$v_x^* = -8S^* (a^* - 2a^* y^* + y^{*2}), \quad (8)$$

where

$$S^* = \sum_{n=1}^{\infty} \frac{n^2 C_n^*}{(1+2na^*)(1+2\delta^*)^n + (1-2na^*)(1+2\delta^*)^{-n}}.$$

It is found that α^* may cause the great part of penetration flow.

2.2 Temperature distribution and thermal resistance

We get, in this section, a solution for temperature distribution using Eq.(8) for penetration flow. The equation of temperature in the fabric must be one which holds in the boundary layer;

$$Ca \rho_a \left(v_x \frac{\partial T}{\partial x} + v_y \frac{\partial T}{\partial y} \right) = \lambda_m \frac{\partial^2 T}{\partial y^2}, \quad (9)$$

where λ_m is the thermal conductivity of fabric defined as a mixture of fiber and air, $Ca \rho_a$ represents the product of the specific heat and density of air. v_x and v_y are the components of penetration flow.

Symmetrical relation with respect to the stagnation point gives the relation at $x=0$;

$$\frac{\partial T}{\partial x} = 0, \quad (10)$$

Considering the above, and introducing a dimensionless form, Eq.(9) becomes

$$v_y^* \frac{dT}{dy^*} = \frac{2\lambda_m \nu}{Ca \rho_a k U^2} \frac{d^2 T}{dy^{*2}}. \quad (11)$$

Since v_y^* is given by the formula (8), the equation to be solved is

$$\frac{d^2 T}{dy^{*2}} + 4k^* P_{rm} R_e^2 S^* \{ a^* + (1-2a^*) y^* \} \frac{dT}{dy^*} = 0, \quad (12)$$

where k^* is the dimensionless permeability, P_{rm} is a modified Prandtl number, and Re is Reynolds number. It is noticed here that the wind velocity is put together with the properties of fabric into a group $k^* P_{rm} Re^2$.

Eq.(12) has a general solution

$$T = -\text{con.} \int e^{-2A((1-2a^*)y^{*2} + 2a^*y^*)} dy^*, \quad (13)$$

where $A = k \cdot \text{Prm} \cdot \text{Re}^2 \cdot S^*$, and con. is an integration constant.

We now define the thermal resistance of fabric layer, I_F , as a ratio of the temperature difference induced across the layer, $T(0) - T(\delta^*)$, to the heat flux density at the surface of heated cylinder, q_w ;

$$I_F = \{T(0) - T(\delta^*)\} / q_w \quad (14)$$

Using the solution for temperature distribution of Eq. (13), $T(0) - T(\delta^*)$ and q_w are described as follows

$$q_w = -\lambda_m \frac{dT}{dy}(0) = \text{con.} \cdot \lambda_m / D, \quad (15)$$

$$T(0) - T(\delta^*) = \text{con.} \int_0^{\delta^*} e^{-2A((1-2\alpha^*)y^2 + 2\alpha^*y^*)} dy^*, \quad (16)$$

Then the resistance I_F is

$$I_F = \frac{D}{\lambda_m} \int_0^{\delta^*} e^{-2A((1-2\alpha^*)y^2 + 2\alpha^*y^*)} dy^*, \quad (17)$$

When there is no penetration in the fabric layer, the value of I_F must be equal to the purely conductive resistance, δ / λ_m , which is, of course, attained if A becomes zero in Eq. (17). I_{F0} denotes this value;

$$I_{F0} = \delta / \lambda_m \quad (18)$$

The wind penetration makes the value of I_F smaller than that of I_{F0} . The reduction of resistance is conveniently indicated by an index number, I_F / I_{F0} . ϵ denotes this index number of resistance of fabric layer;

$$\epsilon = I_F / I_{F0} \quad (19)$$

The index number is written down explicitly, by using Eq. (17) and Eq. (18);

$$\epsilon = \frac{1}{\delta^*} \int_0^{\delta^*} e^{-2A((1-2\alpha^*)y^2 + 2\alpha^*y^*)} dy^*, \quad (20)$$

All the variables in this form are reduced to four independent groups. They are

Fig.2 Theoretical results for thermal resistance of fabric layer

$k \cdot \text{Prm} \cdot \text{Re}^2$, Cn^* , α^* , and δ^* . Among them, Cn^* , the coefficients for pressure distribution are assumed to be constant and independent of Re and the sort of fabric layer; this assumption is based on the experimental results described in §3.1. Then the index number for thermal resistance of fabric layer is a function of three variables as illustrated in Fig.2.

Fig.2 shows that the resistance decreases obviously with an increase of Re . The characteristic number of contact layer α^* plays a great role in the behaviour of resistance decreasing with an increase of Re . The larger the value of α^* for the fabric layer, the more will be the resistance loss therein. And the effect of α^* on the resistance change is quite large for a thin layer.

Overall heat transfer coefficient is denoted by h , and it may be a composite of the resistance of fabric layer and the coefficient, h_A , of heat transfer by the external wind from the fabric surface to the environment;

$$\frac{1}{Dh} = \frac{1}{(D+2\delta)h_A} + \frac{\epsilon\delta}{D\lambda_m} \quad (21)$$

Introducing dimensionless resistances, this equation becomes

$$I^* = I_A^* + I_F^*, \quad (22)$$

where $I^* = \lambda_a / Dh$, $I_A^* = \lambda_a / (D+2\delta)h_A$, and $I_F^* = \epsilon\delta\lambda_a / D\lambda_m$, and they denote the overall resistance, the external air resistance and the fabric layer resistance respectively.

Heat transfer coefficient h_A is assumed to have the same value as that for the surface of a normal, bare cylinder, though that of a covered cylinder is affected by the presence of air flow across the fabric surface. The assumption is partly justified by the pressure distribution around the outer fabric surface and the smallness of penetration flow. The pressure distribution, which is illustrated in §3.1, does not differ so much from that for a normal cylinder and therefore the flow patterns outside the boundary layer will be the same for both cylinders clothed and bare. The penetration flow is not larger than one hundredth of an incident wind flow. Accordingly h_A is estimated, for a cylinder of diameter $D+2\delta$, by using an experimental relation $\text{Nu} = 1.08\sqrt{\text{Re}}$ of a bare heated cylinder in our wind tunnel. Then the thermal resistance I_A^* is

$$I_A^* = 1 / 1.08\sqrt{\text{Re}(1+2\delta^*)} \quad (23)$$

3. Experiment

At first, the measurement of each parameter is described. Then, the heat transfer experiments conducted on four sorts of fabric layer are described.

3.1 Characteristic number of contact layer and pressure distribution

It was found previously that the air passage through the contact layer became less due to the presence of an adhesive material between fabric and cylinder. But the intervention of a third material such

Fig.3 Modes of fitting the fabric systems

as double adhesive tape or adhesive paste should be avoided not to give an uncertainty to the result of heat transfer experiment. Accordingly the characteristic number of contact layer has been varied by degree of hoop stress on the fabric layer.

Most of fabrics readily creep under stress. We have got rid of this phenomenon by adopting elastic bandages as test material or by using elastic braid and hook to fit felt layers. Fig.3 illustrates the ways of fitting fabrics to the cylinder. An elastic bandage adheres to the cylinder at both corners of its beginning, and is wound up with a load at the end. This load determines the hoop stress in the elastic bandage layer. A felt is fitted with some hooks as shown in Fig.3B, and its hoop stress is determined by the magnitude of elongation of the elastic braid of hook.

The pressures caused by wind around these cylinders are measured in the wind tunnel, and the characteristic number of contact layer for each cylinder is deduced by the procedure of the previous paper.

Fig.4 shows the characteristic number for some sorts of covered cylinder. For gauze and for felt of zero load, characteristic numbers vary with wind speed and scatter, but elastic bandages and other felts have a specific constant number for each. For these latter layers, there exist relations between characteristic number and hoop stress as shown in Fig.5. These relations are reproducible within an error of ± 0.05 in the characteristic number for

Material	Load or Tension
○: Felt(1 layer)	0 gf/mm
●: Felt(1 layer)	5 gf/mm
◐: Felt(1 layer)	13 gf/mm
◇: Elastic bandage (3 layers)	0 g/mm
◊: Elastic bandage (3 layers)	0.4 g/mm
◆: Elastic bandage (3 layers)	1.3 g/mm
⌈: Gauze(6 layers)	0 g/mm

Fig.4 Characteristic number of contact layer for some systems fitting to cylinder

Fig.5 Characteristic number of contact layer as a function of hoop-stress for some sorts of fabric material

Fig.6 Pressure distribution around outer circumference of fabric layer

a certain tension or load. The characteristic number around the heated cylinder, which is a different cylinder from the one for measuring the pressure distribution, is estimated according to these relations.

Pressure around the outer circumference of fabric layer shows little difference among different sorts of fabrics, and it does not differ either depending on wind velocities. Fig.6 illustrates some experimental results, and all of them are fairly well expressed by the average distribution. Then Cn^* are given by Fourier expansion of this average distribution. This expression must be approved for the Re range where Newton's resistance law holds.

3.2 Permeability

Pressure distribution of Eq.(1) is affected by k^* implicitly through Cn^* , and Cn^* is said above to be hardly affected by permeability. Then, the permeability does not have much effect on the pressure distribution. But, it has great effect on the penetration rate as well as on the heat transfer coefficient. Therefore, the permeability should be measured more carefully than in the previous study.

Conditions of fabric layer must be the same in the permeability measurements and in the heat transfer experiments. To avoid extra deformations, we use a plastic net cylinder of Fig.7 which has nearly the same diameter as the heated cylinder. Fabrics are fitted to the net cylinder in the manner described in §3.1. Suction rate of air through fabric layer and pressure dif-

Fig.7 Air permeability instrument

ference at that time give a permeability. This result would give more practical value than the Frazier apparatus of the previous paper.

Figs.8 and 9 show the air suction rate and the pressure difference. Hollow symbols denote the measured values at every stage in the process of increasing the flow rate. Solid symbols denote those in the decreasing process. There seems to be no hysteresis between the two processes.

The permeability of elastic bandage increases with an increase of tensile hoop stress, but the permeability of felt remains almost constant because of the cancellation by reduction in its thickness(Table 1).

3.3 Heat transfer and thermal conductivity of fabric

Fig.10 shows a heated cylinder made of brass, with an electric heater of diameter 16mm. Air gap between the brass cylinder and the concentric heater makes the heat

Fig.8 Air flow through felt

Fig.9 Air flow through elastic bandage

Fig.10 Heated cylinder covered with close-fitting fabric, 24mm O.D., 110mm long

flux density uniform over the circumference. 24 slits in the cylinder prevent heat conduction from one segment to another. Then, the radial heat flux at the outer circumference of the cylinder must be uniform.

Temperatures at the cylinder surface are measured with thermo-couples which have their junction at the surface of each segment.

The covering is provided in the manner described in §3.1. Heat transfer experiments are carried out at several magnitudes of wind velocity in the wind tunnel. The results are described in terms of overall heat transfer coefficient, and illustrated in Fig.12.

In terms of the thermal resistance, the results are shown in Fig.11, where the external air resistance I_A^* of Eq.(23) is also described. The resistance of fabric layer I_F^* is calculated by subtracting I_A^* from I^* . If the magnitude of wind becomes small, the penetration becomes small and I_F^* approaches the purely conductive resistance denoted by I_{F0} in §2.2;

$$I_F^* \rightarrow \lambda_a \delta^* / \lambda_m \quad (Re \rightarrow 0)$$

From this relation, thermal conductivity, λ_m , of fabric layer may be estimated by ex-

Fig.11 Variation of thermal resistance with wind velocity

Table 1 Some pertinent data on fabric layers

Material	Number of Layers	Tensile Load or Tension	Thickness	Permeability	Thermal Conductivity
Elastic Bandage	3	0 g/mm	3.0 mm	$0.54/10^{10} \text{ m}^2$	0.13 W/mK
		1.3	2.25	$0.16/10^9$	0.15
Felt	1	5 gf/mm	3.0	$0.16/10^{10}$	0.17
		13	2.75	$0.17/10^{10}$	0.15

trapolating the value of I_p . This estimation is carried out under a perfectly identical condition with the heat transfer experiments, but the accuracy of estimation is not satisfactory.

All the values of fabric layer are tabulated in Table 1.

4. Discussion

4.1 Overall heat transfer coefficient

Eq.(21) gives the overall heat transfer coefficient as a function of the following arguments;

- A) Attributes of wind: wind velocity, properties of air.
- B) Fabric properties: thermal conductivity, permeability.
- C) Geometrical factors: diameter of cylinder, thickness of fabric layer.
- D) Fitting conditions: characteristic number of contact layer.

Calculation for each case of experiments gives each solid line of Nusselt number in Fig.12. If there were no penetration, heat transfer coefficients would be described by each dotted line.

For large Re , solid lines get up from dotted ones on account of heat transfer augmentation by wind penetration.

These lines of theoretical calculation coincide well with experimental data, so the theory is verified.

Fig.12 Measured and calculated heat transfer coefficients at stagnation point; dashed lines indicate values of impermeable layers

4.2 Index number of thermal resistance of fabric layer

The thermal resistance of fabric layer can be obtained from the data. These resistances are rewritten in terms of index number of Fig.2, and shown in Fig.13 with the theoretically estimated lines.

The lower part of Fig.13 includes the results for both a felt and an elastic bandage which happen to have the same values of δ^* and α^* . These different sorts of fabric behave in the same manner that is just predicted by the theory.

In the middle part of Fig.13, two experiments of different runs but of same δ^* and α^* are illustrated. Run 1 has been done at the first stage of our study, and it betrays great awkwardness in experimentation. Scatter and reproducibility in data are the worst of all experiments. But, in terms of overall heat transfer coefficient, the scatter is not remarkable as seen in Fig.12.

In the upper part of Fig.13 the experimental results deviate to the right from the theoretical description, though both are alike in the behaviour of resistance reduction.

Index number ϵ in Fig.13 is a function of α^* , δ^* and Re . δ^* has been investigated in a narrow range of 0.09 to 0.12, and then the three lines do not clearly show the effect of δ^* . The difference between them is chiefly caused by α^* , and it has been found in §2.2. that the line should be shifted to the left with an increase of α^* . Fig.13 proves this statement; the lower line of the figure has a larger value of α^* and is shifted to the left in accordance with the experimental data.

The nature of heat transfer from the covered cylinder has been understood to a

Fig.13 Measured and calculated index numbers of thermal resistance of fabric layer

Fig.14 Increase of thermal resistance with increase of fabric layer thickness calculated at $k \cdot \text{Prm} \text{Re}^2 = 10$; Straight line indicates value of impermeable layer.

great extent, but there is a little quantitative disagreement recognized between theoretical values and data. We now deal with some potential causes of this disagreement.

The real value of external resistance, I_A , must be less than the estimate in §2.2 owing to a radial flow caused by penetration.

Slits in a heated cylinder cause ripples on the surface, although they are filled with epoxyresin and made flush with the surface. These ripples make the occurrence of air flow in the contact layer somewhat difficult, then the characteristic number α^* would be smaller than the estimate value. If α^* were a half of estimate, the calculated values of ε would come close to the experimental values; they come so close that the systematic deviation in Fig. 13 might be brought about by an error of α^* . Heat flux density is not so large in comparison with the one on human body and the temperature difference between the cylinder surface and the environmental air remains 10 to 20K. To measure more accurately the change of heat transfer coefficient with wind velocity, a larger heat flux would be required.

4.3 Effect of thickness and contact layer

Fig.2 shows that a thicker layer loses resistance more easily. It might mislead us to conclude that the thickness of layer would have no advantage. Fig.14 is more convenient for us to understand the effect of thickness.

The ordinate of Fig.14 is the resistance I_f , which is made dimensionless, and it is described with an argument δ^* , and a parameter α^* , at a modified wind velocity of fixed value. The resistance of fabric increases with an increase of thickness, but it is not proportional to the thickness. A layer of double thickness has generally less than double resistance. This nature of

thickness is a result of penetration which easily erode a far part of layer off the cylinder.

The effect of penetration may be made negligibly small, if we use a thin layer and make α^* small. It is seen in Fig.14 that a layer of $\alpha^*=0$ has an almost pure conductive resistance up to $\delta^*=0.05$.

The contact layer is revealed to be an important factor to maintain the fabric resistance.

We consider solely the layer closely fitting to cylinder, and the concept of contact layer for this case should be extended further to an air layer between fabric and human body. The air layer is supposed to damage thermal insulation. However the air layer is often said to be useful to assume effective warmth of clothing. It is obviously true that any air layer is advantageous in case of no convection. In case of wind, the air layer could augment the wind penetration into the fabric layer, and we should need some devices to take advantage of the air layer, e.g. spaced wind breaks proposed by Fonseca et al.⁽³⁾.

5. Conclusions

In connection with the thermal insulation test of materials for clothing in wind, the heat transfer has been studied using a cylinder covered with close-fitting fabrics, and the followings are concluded;

- (1) In the state described as "close-fitting", there are various degrees of fitting, and the degree is measured by a characteristic number of contact layer α^* . α^* has a great effect on penetration and heat transfer.
- (2) The thermal resistance of fabric layer is given by Eq.(20), as illustrated in Fig.2. The resistance is affected by the wind velocity, the permeability of fabric, and the thermal conductivity of fabric. They are grouped into an argument, $\text{Re}/k \cdot \text{Prm}$. The other complementary parameters are δ^* and α^* .
- (3) Fig.13 shows the overall heat transfer coefficient. The theoretical estimation describes the experimental feature well.

Acknowledgement

The authors wish to thank Professor Y.Kurosaki and Mr.M.Suzuki for their support to this investigation.

References

- (1) Takeuchi, M., et al., Bull. of the JSME, 25-207 (1982-9), 1406.
- (2) Katto, Y. and Masuoka, T., Trans. Japan Soc. Mech. Engrs. (in Japanese) 32-243 (1969), 1708.
- (3) Fonseca, G.F. and Breckenridge, J.R., Tex. Res. J., 35-2 (1965), 95.