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A correlation of maximum turbulent heat transfer coefficient in reattachment flow region

TERUKAZU OTA
Department of Mechanical Engineering, Faculty of Engineering, Tohoku University, Sendai 980, Japan

and

HIDEYA NISHIYAMA
Department of Mechanical and Production Engineering, Akita University, Akita 010, Japan

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Abstract—A correlation of the maximum turbulent heat or mass transfer coefficient in the reattachment region of separated flow is proposed based on surveying thoroughly previous data and also on conducting heat transfer measurements. A newly proposed formula is expressed by

$$\frac{h_R l}{\lambda} = 0.192\left(\frac{U_s l}{\nu}\right)^{0.665} Pr^{1/3}$$

in which h_R, l, U_s and Pr denote the maximum heat transfer coefficient, the streamwise distance from the separation point to the reattachment point, the velocity along the separated shear layer and Prandtl number, respectively. In the case of mass transfer, Pr and λ are to be replaced by Sc and D, which are the Schmidt number and diffusion coefficient, respectively. That formula is found to be valid in a range of $0.7 \leqslant Pr \leqslant 9$, $0.6 \leqslant Sc \leqslant 2500$ and $8 \times 10^3 \leqslant U_s l/\nu \leqslant 2 \times 10^6$.

1. INTRODUCTION

PREDICTION of heat and mass transfer in the separated, reattached, and redeveloped regions of incompressible or compressible flow is very important in relation to many types of heat exchangers, and there have been numerous works on a wide variety of flow configurations. Examples include abrupt circular channel expansions including orifice induced separations [1–16], downward surface steps [17–22], blunt bodies [23–38] and roughness elements attached to flat surfaces [39–44]. Many of these works have been cited in review papers by Chilcott [45] and Fletcher *et al.* [46]. Furthermore, several reports have recently been published [47–60].

It has been clarified from these previous studies that the turbulent heat or mass transfer coefficient reaches a maximum in the reattachment region of the separated flow. It has also been found that at the critical state of flow around bluff bodies such as circular and elliptic cylinders, the boundary layer separates laminarly, the separated shear layer transits to the turbulent one and subsequently reattaches to the surface where the heat transfer coefficient attains a maximum [61–65].

It has been noticed that the flow structure in the separated and reattached regions is extremely complicated and the details of the heat transfer mechanism are not clarified at present. Accordingly, correlations of the maximum heat transfer coefficient have mostly been obtained separately for individual flow configurations by the authors. Under such a situation, the present authors have shown that the reattachment length is suitable as the characteristic length to correlate the maximum heat transfer coefficient with the Reynolds number for different flow configurations [31, 32].

The purpose of this paper was to propose a new universal correlation formula of the maximum turbulent heat or mass transfer coefficient with physical parameters such as Reynolds number and Prandtl or Schmidt number, which may have an applicability to a wide variety of flow configurations and fluids. Such a correlation may be very useful to understand the turbulent heat transfer mechanism in the separated and reattached flow regions.

2. EXPERIMENTS

The present experiments were conducted to obtain the data especially at relatively low Reynolds numbers for supplementing previous data by the present authors [32, 35]. The wind tunnel and the blunt flat plates having various nose shapes were the same as in the previous studies. Therefore, their details are omitted in this paper. In addition to the heat transfer measurements, the streamwise mean and turbulent fluctuating velocities were measured with a constant temperature hot-wire anemometer, though the plate surface was not heated. Some details of these data have been reported elsewhere [66].

It may be reasonable to consider that the heat transfer characteristics in the reattachment flow region

NOMENCLATURE

D	diffusion coefficient
$2H$	plate thickness
h	heat transfer coefficient, $q/(T_w - T_\infty)$
h_R	maximum heat or mass transfer coefficient in reattachment region
l	distance from separation point to reattachment point
Pr	Prandtl number
q	heat flux per unit area and unit time
Re	Reynolds number, $U_\infty H/\nu$
Sc	Schmidt number
T_w	wall temperature
T_∞	temperature at upstream uniform flow
U_s	velocity along separated shear layer
U_∞	velocity at upstream uniform flow.

Greek symbols

α	apex angle of wedge
λ, ν	thermal conductivity and kinematic viscosity of fluid.

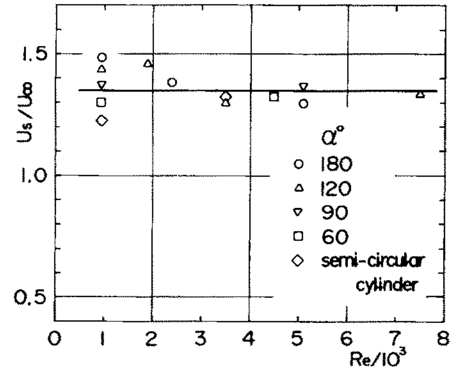

FIG. 1. Velocity along the separated shear layer over blunt flat plates.

depend greatly upon the behavior of the separated shear layer. Results represented in Fig. 1 are the maximum velocity of the separated shear layer for the blunt flat plates having various nose shapes. It may be regarded that the non-dimensional velocity U_s/U_∞ of the separated shear layer is essentially constant independent of the nose shape, the value of which is nearly equal to 1.35. Results of the maximum heat transfer coefficient will be shown in the following section in relation to the correlation formula.

3. PROPOSAL OF CORRELATION FORMULA

In order to propose a universal correlation formula with high reliability, it is very important to collect data having as high certainty as possible. Table 1 tabulates the previous studies by several authors. It includes the flow configuration, the testing fluid and also the measuring method. Many of the studies cited are the heat transfer ones, though those followed by the symbol MT are the mass transfer ones.

References [1–16] are concerned with abrupt circular channel expansions and orifice induced separations, refs. [17–22] are the downward surface steps, refs. [23–38] the blunt bodies and refs. [39–44] the roughness elements attached to the flat surfaces, respectively. Furthermore, several papers have recently been published. That is, the abrupt circular channel expansion has been studied in refs. [47–49], the downward step in refs. [50–57], the rectangular prism in ref. [58] and the bluff bodies located on a flat surface in refs. [59, 60]. In many of these works, the main purpose, however, seems to consist of obtaining the heat or mass transfer characteristics while the velocity and temperature fields have not been investigated. In the course of estimating the correlation formula in the present study, only the data, in which the velocity U_s along the separated shear layer, the distance l from the separation point to the reattachment one and the physical properties are definitely described in the paper, are referred.

Heat transfer characteristics in the reattachment region of the separated flow are reasonably considered to depend strongly upon the characteristic behavior of the separated shear layer therein. There are some reports, in which the position of the maximum heat transfer coefficient is located somewhat upstream of the time-averaged reattachment point. However, this difference is generally small. Furthermore, many of the previous works have described that the position of the maximum heat transfer coefficient is essentially in agreement with that of the time-averaged reattachment point. Accordingly in the present study, it is considered that both of them agree with each other.

In estimating a correlation formula between the maximum turbulent heat transfer coefficient in the reattachment region and the Reynolds number, which determines the flow characteristics definitely, the distance l may be the most suitable reference length in the Nusselt and Reynolds numbers, since it indicates an order of the diffusion of the separated shear layer. On the other hand, the velocity U_s may be the best reference velocity in the Reynolds number, since the heat transfer rate near the reattachment region depends greatly upon the convection velocity therein.

In this and previous studies by the authors, the velocity along the separated shear layer was measured. However, in many of the published papers, it was not measured. Therefore, in the flow through the circular channel expansion and the orifice, the mean velocity at the cross-section of the flow separation is regarded

Table 1. Published papers on heat or mass transfer in separated and reattached flow. Journal titles are abbreviated for space limitation and their details are cited in the references

Ref.	Author	Journal	Configuration	Fluid	Method
1	Amano *et al.*	*JHT* **105**, 1983	abrupt pipe expansion	liquid R113	
2	Caton	*JHT* **105**, 1983	exhaust pipe	air	
3	Ede *et al.*	*PIME* **38**, 1956	abrupt pipe convergence and expansion	water	
4	Filetti and Kays	*JHT* **89**, 1967	double step	air	
5	Kawashima *et al.*	*Kagaku Kogaku Ronbunshu* **7**, 1981	T-shaped duct	air	
6	Koram and Sparrow	*JHT* **100**, 1978	unsymmetric pipe blockage	water	
7	Krall and Sparrow	*JHT* **88**, 1966	pipe with orifice	water	
8	Martin and Koeut	*HT-1978*, **5**, 1978	double step	air	
9	Runchal	*IJHMT* **14**, 1971	abrupt pipe expansion	liquid	MT
10	Seki *et al.*	*IJHMT* **19**, 1976	double step	air	
11	Seki *et al.*	*JHT* **98**, 1976	double step	air	
12	Sparrow and Cur	*JHT* **104**, 1982	rectangular duct	air	MT
13	Sparrow and Kemink	*IJHMT* **22**, 1979	T-shaped pipe	air	
14	Suzuki *et al.*	*Trans. J.S.M.E.* **B48**, 1982	pipe with orifice	air	
15	Wesley and Sparrow	*IJHMT* **19**, 1976	T-shaped pipe	air	
16	Zemanick and Dougall	*JHT* **92**, 1970	abrupt pipe expansion	air	
17	Aung and Goldstein	*HT-1970*, **2**, 1970	downstep	air	
18	Kottke	*Chemie–Ingr.–Tech.* **54**, 1982	downstep	air	MT
19	Kottke and Blenke	*VDI Forsch. Ing.* **49**, 1983	downstep	air	MT
20	Nakamaru *et al.*	17th Nat. Heat Transf. Symp. Japan, 1980	downstep	water	
21	Seban	*JHT* **86**, 1964	downstep	air	
22	Seban *et al.*	*J. Aerospace Sci.* **26**, 1959	downstep	air	
23	Cooper *et al.*	Proc. 8th Australasian Fluid Mech. Conf.	blunt flat plate	air	
24	Daigo *et al.*	9th Nat. Heat Transf. Symp. Japan, 1972	normal plate with splitter	air	
25	Igarashi	*Trans. J.S.M.E.* **B50**, 1984	square prism	air	
26	Kottke *et al.*	*Wärme Stoff.* **10**, 1977	blunt flat plate	air	MT
27	Kottke *et al.*	*Wärme Stoff.* **10**, 1977	blunt flat plate	air	MT
28	Nabemoto and Chiba	16th Nat. Heat Transf. Symp. Japan, 1979	blunt flat plate	air	
29	Nabemoto and Chiba	17th Nat. Heat Transf. Symp. Japan, 1980	blunt flat plate	air	
30	Ota and Kon	*JHT* **96**, 1974	blunt flat plate	air	
31	Ota and Kon	*JHT* **99**, 1977	blunt circular cylinder	air	
32	Ota and Kon	*IJHMT* **22**, 1979	blunt flat plate	air	
33	Ota and Kon	*JHT* **102**, 1980	blunt flat plate	air	
34	Ota *et al.*	*Bull. J.S.M.E.* **23**, 1980	blunt circular cylinder	air	
35	Ota *et al.*	*Bull. J.S.M.E.* **23**, 1980	blunt flat plate	air	
36	Smyth	*Lett. HMT* **6**, 1979	circular disc with rod	air	
37	Sørensen	*Chem. Engng Sci.* **24**, 1969	blunt flat plate	air	MT
38	Zysina-Molozhen and Dergach	*HT—Soviet Res.* **13**(5), 1981	airfoil cascade	air	
39	Fujita *et al.*	*Trans. J.S.M.E.* **42**, 1976	cylinder on flat plate	air	
40	Luzhanskiy and Solntsev	*HT—Soviet Res.* 3(6), 1971	forward step	air	
41	Miyashita *et al.*	*Kagaku Kogaku Ronbunshu* **6**, 1980	cylinder on flat plate	air	MT
42	Mori and Daikoku	*Trans. J.S.M.E.* **38**, 1972	cylinder on flat plate	air	MT
43	Seban and Caldwell	*JHT* **90**, 1968	sphere on flat plate	air	
44	Solntsev *et al.*	*HT—Soviet Res.* **5**(2), 1973	sudden step	air	

as U_s. In the case of the flow over the downward step, the free stream velocity outside the boundary layer at the step is estimated as U_s. For the flow around bluff bodies, U_s was estimated from the pressure coefficient C_{ps} in the separation bubble by $U_s = U_\infty\sqrt{(1-C_{ps})}$, when it was not measured. There have been many works on the heat transfer around the roughness elements of various shapes. The velocity field, however, was not measured in many of them. In such a flow situation, it is not easy to estimate U_s. Therefore, many of the published data on the roughness elements have not been cited in estimating the correlation formula.

To determine the correlation formula 276 data points were finally used. Represented in Fig. 2 are those data along with the correlation formula newly proposed in the present study

$$\frac{h_R l}{\lambda} = 0.192\left(\frac{U_s l}{\nu}\right)^{0.665} Pr^{1/3}. \qquad (1)$$

In the case of mass transfer, Pr and λ are replaced by Sc and D, respectively, in equation (1). At a Reynolds number lower than about 8000, a deviation of the data from equation (1) seems to grow. It may be considered that in such a situation, the flow separates laminarly and the separated shear layer transits to the turbulent one upstream of the reattachment point. That is, the flow may be included in the so-called transition region. In the present study, the main purpose was to propose the universal correlation formula of the reattachment maximum heat transfer coefficient, in which the flow separates in the turbulent state and the turbulent shear layer reattaches to the body surface. Under such a flow situation, the heat transfer characteristics exhibit no essential dependency upon the Reynolds number. Accordingly the data at a Reynolds number lower than about 8000 were not employed in the estimation of equation (1). Furthermore, four data points by Smyth [36] deviate systematically from other ones. These were also omitted in the estimation of equation (1). Equation (1) is effective in the range of

$$8\times10^3 \leqslant U_s l/\nu \leqslant 2\times10^6$$

$$0.7 \leqslant Pr \leqslant 9$$

$$0.6 \leqslant Sc \leqslant 2500.$$

Deviation of the data from equation (1) is estimated to be at most about 38.5% in the figure.

It is also possible to estimate the certainty of the proposed formula by comparing other published data, though they are not included in Fig. 2. Kasagi and co-workers [20, 50] measured the heat transfer in the flow over a downward step using air and water. It is found that the data using air agree well with equation (1) though those using water deviate considerably. Maeda *et al.* [51] studied the heat transfer in a gas–solid two-phase flow over a downward step. Their data are detected to be in fairly good agreement with equation (1), even though solid particles are included in the air flow. McCormick *et al.* [58] made an experimental study on the heat transfer from a rectangular prism in air flow. Their data are well correlated by equation (1). Its largest deviation is found to be about 36.7%. Baughn *et al.* [49] measured the heat transfer in the flow of air downstream of a circular channel expansion. Their data are also found to be in good agreement with equation (1).

As previously noted, in the critical flow around the circular and elliptic cylinders, a small separation bubble is formed and the heat transfer coefficient reaches a maximum at the reattachment point of the turbulent separated shear layer. It may not be unreasonable to suppose that the heat transfer mechanism in the reattachment region is basically similar to that discussed above. Though the number of heat transfer data published up to this time is quite small, an attempt has been made in order to estimate the appropriateness of equation (1). The results are represented in Fig. 3. The data by Giedt [61, 62] and Achenbach [63, 64] are related to the flow around a circular cylinder and those by the present authors to that around an elliptic cylinder having an axis ratio of 1 : 3 [65]. It is not easy to estimate the velocity along the separated shear layer since it is located very close to the cylinder surface. Accordingly in the present study, U_s is calculated from the pressure distribution in the separation bubble by $U_s = U_\infty\sqrt{(1-C_{ps})}$, in the same way for the bluff bodies described previously. It is found that the results show at least qualitatively the same trend as equation (1), though the number of data is small and its scatter is large. An average line included in Fig. 3 is

$$\frac{h_R l}{\lambda} = 0.10\left(\frac{U_s l}{\nu}\right)^{0.665} Pr^{1/3}. \qquad (2)$$

4. DISCUSSION

In the course of estimating the correlation formula, the power of the Prandtl or Schmidt number was varied from 1/3 to 0.4, which has also been widely used in the literature. However, the power of 1/3 was detected to correlate the data better than 0.4. Therefore, in this paper, the results using the power of 1/3 are represented. It may, of course, be necessary to refine its value based on the minute experiments using a wide variety of fluids.

There have been some data, which deviate systematically from equation (1), though the number of such data is relatively small, as previously described. The certainty of the newly proposed formula, equation (1), is necessarily based on the measured data using a wide variety of flow configurations and also of fluids. However, based on the comparisons shown in Fig. 2, it seems to be reasonable to consider that the heat or mass transfer mechanism in the reattachment region is essentially independent of the flow configuration and of the fluid, at least, in the range of

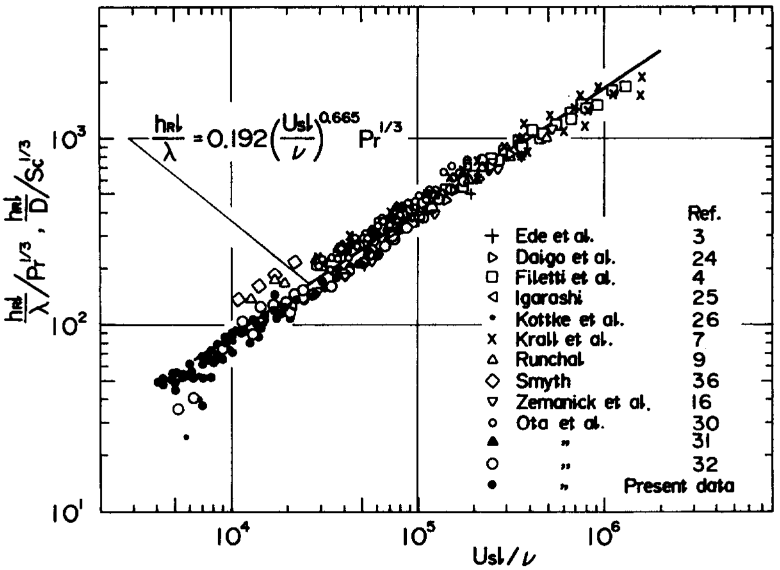

FIG. 2. Correlation of the maximum turbulent heat transfer coefficient in the reattachment region.

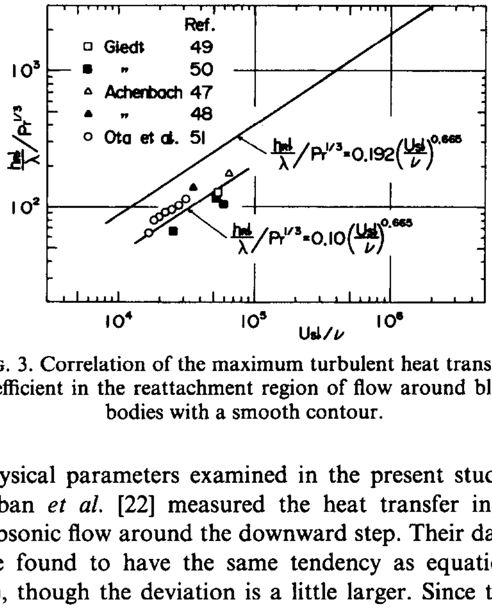

FIG. 3. Correlation of the maximum turbulent heat transfer coefficient in the reattachment region of flow around bluff bodies with a smooth contour.

physical parameters examined in the present study. Seban *et al.* [22] measured the heat transfer in a subsonic flow around the downward step. Their data are found to have the same tendency as equation (1), though the deviation is a little larger. Since the physical properties are not clear, their data are not included in Fig. 2. In accordance with these results, equation (1) may be applicable to Reynolds number higher than 2×10^6.

The results shown in Fig. 3 suggest that the basic concept proposed in the present study for the maximum turbulent heat transfer coefficient in the reattachment flow region may be applicable to the flow around bluff bodies having a smooth contour such as a circular cylinder and an elliptic cylinder. The detailed measurement of the velocity along the separation bubble may make the certainty of equation (1) clear.

5. CONCLUDING REMARKS

There are so many cases in which the flow separates from the surface in the turbulent state or the laminar separated shear layer transits immediately to the turbulent one and the turbulent shear layer reattaches to the boby surface. Investigated in this paper is the maximum turbulent heat transfer coefficient in the reattachment flow region.

Through surveying thoroughly the data published in the literature and conducting heat transfer experiments, a universal correlation formula is proposed for the maximum heat or mass transfer coefficient, which is expressed by equation (1). Its certainty and applicable range are discussed in detail in relation to the data referred. Furthermore, the basic concept proposed is applied to the critical flow around bluff bodies having a smooth contour. The results show that the heat transfer mechanism in such a flow situation seems to be basically the same as that found in the separated and reattached flow around or inside bodies having a sharp corner where the flow separates inevitably.

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EXPRESSION DU COEFFICIENT MAXIMUM DE TRANSFERT THERMIQUE TURBULENT DANS LA REGION DE RECOLLEMENT

Résumé—Une formulation du coefficient maximum de transfert massique ou thermique turbulent dans la région de recollement d'un écoulment séparé est proposée à partir de l'examen attentif des données expérimentales. Une expression nouvelle est donnée par

$$\frac{h_R l}{\lambda} = 0{,}192\left(\frac{U_s l}{\nu}\right)^{0{,}665} Pr^{1/3}$$

dans laquelle h_R, l, U_s et Pr expriment le coefficient maximal de transfert thermique, la distance longitudinale entre le point de séparation et celui de recollement, la vitesse le long de la couche limite décollée et le nombre de Prandtl. Dans le cas du transfert massique, Pr et λ sont remplacés par Sc et D qui sont le nombre de Schmidt et le coefficient de diffusion. Ceci est valable dans le domaine $0{,}7 \leqslant Pr \leqslant 9$, $0{,}6 \leqslant Sc \leqslant 2500$ et $8.10^3 \leqslant U_s l/\nu \leqslant 2.10^6$.

KORRELATION DES MAXIMALEN TURBULENTEN WÄRMEÜBERGANGSKOEFFIZIENTEN IM WIEDERANLEGEGEBIET EINER ABGELÖSTEN STRÖMUNG

Zusammenfassung—Es wird eine Korrelation für den maximalen turbulenten Wärme- und Stoffübergangskoeffizienten für das Wiederanlegegebiet einer abgelösten Strömung vorgeschlagen. Die Grundlage dafür bildet eine gründliche Analyse der bereits vorhandenen Daten, außerdem eigene Messungen des Wärmeübergangs. Die neu vorgeschlagene Gleichung lautet:

$$\frac{h_R l}{\lambda} = 0{,}192\left(\frac{U_s l}{\nu}\right)^{0{,}665} Pr^{1/3},$$

wobei h_R den maximalen Wärmeübergangskoeffizienten, l den Abstand zwischen Ablöse- und Wiederanlagepunkt, U_s die Geschwindigkeit entlang der trennenden Scherschicht und Pr die Prandtl-Zahl bezeichnen. Im Fall des Stofftransports werden Pr und λ durch die Schmidt-Zahl Sc und den Diffusionskoeffizienten D ersetzt. Die Gleichung ist im Bereich von $0{,}7 \leqslant Pr \leqslant 9$, $0{,}6 \leqslant Sc \leqslant 2500$ und $8 \cdot 10^3 \leqslant U_s l/\nu \leqslant 2 \cdot 10^6$ gültig.

КОЭФФИЦИЕНТ МАКСИМАЛЬНОГО ТУРБУЛЕНТНОГО ТЕПЛОПЕРЕНОСА В ОБЛАСТИ ПРИСОЕДИНЕНИЯ ПОТОКА

Аннотация—На основании анализа имеющихся данных и измерений кондуктивного теплопереноса предложено выражение для коэффициента максимального турбулентного теплопереноса в области присоединения отрывного потока:

$$\frac{h_R l}{\lambda} = 0{,}192\left(\frac{U_s l}{\nu}\right)^{0{,}665} Pr^{1/3}$$

где h_R, l, U_s и Pr—максимальный коэффициент теплопереноса, расстояние от точки отрыва до точки присоединения, скорость вдоль отрывного сдвигового слоя и число Прандтля, соответственно. В случае массопереноса параметры Pr и λ следует заменить на Sc и D (число Шмидта и коэффициент диффузии, соответственно). Показано, что аналогия справедлива для $0{,}7 \leqslant Pr \leqslant 9$, $0{,}6 \leqslant Sc \leqslant 2500$ и $8 \cdot 10^3 < U_s l/\nu < 2 \cdot 10^6$.