TECHNICAL NOTE

Mass transfer measurements from a blunt-faced flat plate in a uniform flow

K. S. Hwang, H. J. Sung, and J. M. Hyun

Department of Mechanical Engineering, Korea Advanced Institute of Science and Technology, Kusong-dong, Yusong-ku, Taejon, South Korea

Introduction

Flow about a blunt-faced body, placed in a uniform stream, has been extensively studied in recent years. In particular, as a benchmark configuration, much work has been reported for a two-dimensional (2-D), semi-infinite flat plate of finite thickness, which is aligned parallel to a uniform approaching stream (Cherry et al. 1984; Kiya and Sasaki 1983, 1985; Ota and Kon 1974, 1980). The canonical flow structure includes a variety of essential dynamical elements (see Figure 1a). The flow separates at the sharp corner of the blunt face, and this separated flow reattaches at a downstream location on the surface of the plate. This forms the well-known pattern of a separation bubble. Farther downstream of the reattachment, the flow undergoes a region of redevelopment, and the overall flow exhibits extremely complex characteristics afterward. One major objective of prior endeavors was to describe both steady and unsteady features of the shedding of the large-scale vortices from the separation bubble (Cherry et al. 1984; Kiya and Sasaki 1983, 1985; Ota and Kon 1974, 1980).

A perusal of the relevant literature reveals that studies of the attendant heat/mass transport phenomena of this flow configuration are scarce (Ota and Kon 1974). This lack of published work may stem from the difficulties associated with detailed measurements of transfer properties in the separated and reattaching zones. However, an in-depth understanding of the transport phenomena about a blunt body is important for a more complete picture of the global flow processes as well as for practical applications. Accurate depictions of the flow structure and transfer characteristics in the immediate neighborhood of the blunt body are essential for design and operation of high-performance fluid machinery. The present note addresses this technical issue.

For the standard flat-plate geometry (see Figure 1a), Ota and Kon (1974) conducted heat transfer experiments using an air stream, in the Reynolds number range $2720 < \mathrm{Re}_H < 17,900$, in which $\mathrm{Re}_H \equiv U_\infty H/\nu$, and ν denotes the kinematic viscosity,

under the condition of a constant heat flux. It was shown that the properly defined heat transfer coefficient reaches a maximum in the reattachment zone. As noted earlier, it seems that no other independent reports have appeared in the published literature that deal explicitly with the transfer properties for the flat-plate configuration.

The present note aims to depict the variation of the local mass transfer coefficient, by employing the naphthalene sublimation technique, on the surface of the flat plate. As established previously (Sung et al. 1994), this experimental method allows higher accuracies in measuring the transfer coefficient in comparison to the corresponding heat transfer experiments. Direct measurements of the local Sherwood number Sh were made in the present experiment for the case when the surface of the plate is maintained at a constant concentration. This is equivalent to the condition of a constant temperature surface in the case of heat transfer experiment.

The naphthalene sublimation technique has been refined for precise measurements of mass transfer, and the full implications of the method have been thoroughly documented (Sung et al. 1994). The mass transfer coefficient h_m can be derived as follows;

$$h_m = \rho_s(\Delta t/\Delta \tau)/\rho_{v,w} \qquad (1)$$

in which ρ_s and $\rho_{v,w}$ denote, respectively, the density of naphthalene and the naphthalene vapor concentration at the wall. Here Δt represents the thickness of the naphthalene sublimation during the time period of $\Delta \tau$. It then follows that the Sherwood number Sh is given as follows;

$$\mathrm{Sh} = h_m H/D_f \qquad (2)$$

in which D_f is the diffusivity of naphthalene. Explicit details, including the relationship between $\rho_{v,w}$ and the local temperature T, are available (e.g., Sung et al. 1994).

The range of Re_H considered in the present experiments was $1200 \leq \mathrm{Re}_H \leq 8000$. In summary, the intention of the present efforts is to secure the baseline experimental data on mass transfer for a blunt-faced flat plate.

Experimental particulars

An open-circuit blower-type wind tunnel was constructed. The air speed in the test section (250 mm × 250 mm) U_∞ varied from 1.5

Address reprint requests to Prof. J. M. Hyun, Department of Mechanical Engineering, Korea Advanced Institute of Science and Technology, Yusong-ku, Taejon 305-701, South Korea.
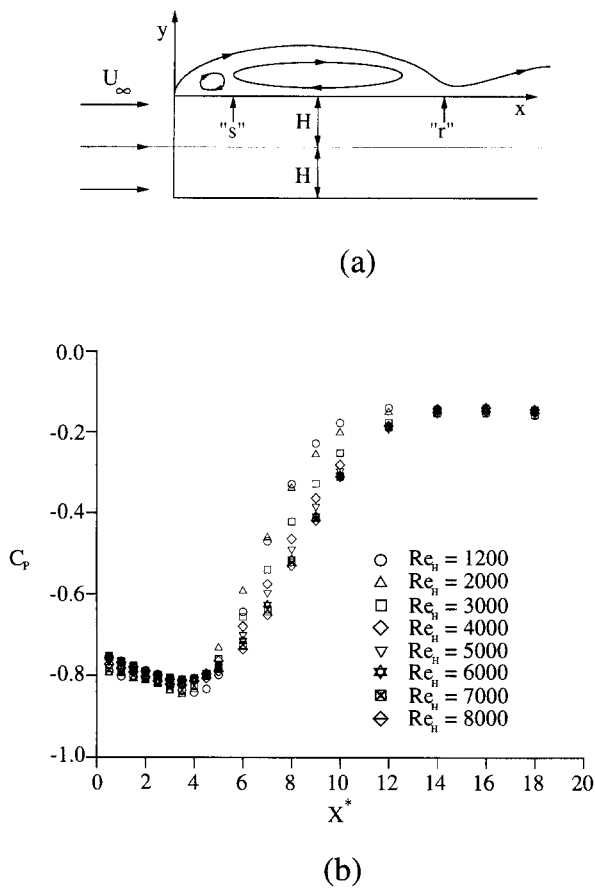
(a)

(b)

Figure 1. (a) A schema of flow configuration; "s" denotes the secondary separation point, and "r" the reattachment point; (b) surface pressure distribution c_p vs. X^* [$\equiv X/H$]

to 12.0 m/s, and the turbulent intensities of the free stream were less than 0.3% (Sung et al. 1994). The flat plate, which was fabricated of Plexiglas®, was 20-mm thick, 250-mm wide, and 550-mm long. This gave a blockage ratio of 7.5%, and the width/height aspect ratio was 12.5. The leading edge of the flat plate was precision machined to be perpendicular to the oncoming stream, and it was placed 450 mm downstream of the inlet of the test section. At the centerline of the upper surface of the plate, a total of 42 pressure taps of 0.8-mm diameter were fitted for the measurements of static pressure on the surface of the flat plate. The mean velocity distribution was measured by means of a standard pitot tube. The turbulent intensity of the free stream was monitored by utilizing an I-type hot-wire.

Care was exercised in dealing with the naphthalene sublimation technique, which formed the heart of the present mass transfer experiments. The portion of the plate, which was naph-

thalene-cast, was finished to ensure that it had the same roughness and thickness as the rest of the steel plate. To measure the sublimated naphthalene, an automated data acquisition system was installed. The main components were a depth gauge with a signal conditioner, a digital voltmeter connected to a GPIB interface, a positioning apparatus driven by stepper motors, and an IBM-486 personal computer. The streamwise variation of the naphthalene sublimation thickness was determined by employing a depth gauge. Prior to each reading, the gauge was allowed a 0.5-s stabilization period. The measurement of the naphthalene surface profile was performed at a constant room temperature, which would alleviate possible errors caused by natural convection.

In the present experiment, the effect of the blockage ratio was reasonably small (Cherry et al. 1984), and the flow at the centerline could be considered two-dimensional (2-D) (Cherry et al. 1984; Kiya and Sasaki 1983, 1985). Strict adherence to the well-documented naphthalene sublimation technique (Sung et al. 1994) was made.

Results and discussion

First, in order to establish the credibility of the present measurements, the time-mean surface pressure distribution with X^* [$\equiv X/H$] is compared with the existing data (Cherry et al. 1984; Kiya and Sasaki 1983, 1985; Ota and Kon 1974, 1980). As shown in Figure 1b, the present data satisfactorily reproduce the characteristic features of the pressure distribution $c_p[\equiv (p - p_\infty)/0.5\rho U_\infty^2]$. It is notable that the c_p curves tend to become independent of Re_H when Re_H exceeds approximately 6000. In the lower range of Re_H, the c_p curves show a mild dependence on Re_H in moderate downstream regions $5.0 < X^* < 12.0$. Also, as Re_H decreases, the pressure recovery zone is seen to be pulled upstream; this implies that the separation bubble shrinks (or is reduced in size). Alternatively, this indicates that the reattachment zone is shifted upstream as Re_H decreases.

The present mass transfer measurements are shown in Figure 2a, which reveals that the streamwise profiles of local Sherwood number Sh contain a minimum at a short distance X_i^* behind the leading-edge corner ($X^* = 0$). In the region between the leading edge and X_i^*, the Sherwood number decreases monotonically with X^*, and the rate of decrease of Sh becomes more conspicuous as Re_H increases. After passing the minimum, the Sh curve increases with X^* until it hits a maximum at a moderate downstream location X_a^*. At farther downstream locations, Sh gradually decreases with X^*. The rate of spatial variations of Sh tends to steepen as Re_H increases.

The existence of a minimum point of the Sh curve is informative, and it warrants a physical explanation in conjunction with the flow field analysis. Kiya and Sasaki (1983), by offering a detailed picture of the flow structure, demonstrated that the velocity is non-zero very close to the leading edge ($X^* = 0$). On

Notation

c_p	pressure coefficient [$\equiv (p - p_\infty)/0.5\rho U_\infty^2$]
D_f	diffusivity of naphthalene
H	half thickness of the plate
h_m	local mass transfer coefficient
Re_H	Reynolds number ($\equiv U_\infty H/v$)
Sh	Sherwood number ($\equiv h_m H/D_f$)
Δt	naphthalene sublimation thickness
U_∞	free-stream velocity

X^*	nondimensional streamwise distance from the leading edge ($\equiv X/H$)

Greek

$\Delta \tau$	exposure time
v	kinematic viscosity
ρ	density of air
ρ_s	density of solid naphthalene
$\rho_{v,w}$	naphthalene vapor concentration at the wall

the other hand, as sketched in Figure 1a, within the fore portion of the separation bubble, a strong reverse flow is seen in the areas spanning moderate downstream locations. Therefore, the non-zero forward flow immediately behind the leading edge and this reverse flow meet at a very short distance from the leading edge (marked by "s" in Figure 1a). Kiya and Sasaki (1983) elaborated that, because of the meeting of these two oppositely directed streams, the surface velocity around point "s" becomes very small (practically zero). This point was termed the secondary separation point (Kiya and Sasaki 1983). It follows that convective activities are minimal around this secondary separation point, which turns up in the form of a local minimum point in the Sh curves of Figure 2a. The above physical argument concerning the local minimum of Sh at X_i^* is qualitatively consistent with the depiction of the global flow patterns advanced by Kiya and Sasaki (1983). It is also worth mentioning that, as Re_H increases, "s" moves to an upstream point. This implies that, as Re_H increases, the reverse flow intensifies, which results in the shift

of the secondary separation point to a farther upstream location, and thus X_i^* moves upstream.

The maximum of Sh, which is seen at a moderate distance X_a^* is associated with vigorous convective activities around the reattachment point. In Figure 1a, this point is marked "r." In this region, intense velocity fluctuations are seen; these wash out the surface, and fresh fluids are entrained toward the surface area. These give rise to transport enhancements. The occurrence of a maximum transfer coefficient at the reattachment point has been amply ascertained in the much-studied backward-facing step flows (Vogel and Eaton 1985). Figure 2a illustrates that, as Re_H increases, X_a^* moves to a location farther downstream. This is in line with the assertion that, as Re_H increases, the flow reattachment takes place at a point farther downstream.

Guided by the earlier experimental correlation of Ota and Kon (1974), it was found that the present data produced a resonable single fit when they were replotted by using $Sh/Re_H^{2/3}$ as the ordinate, as displayed in Figure 2(b). Evidently, the data for high
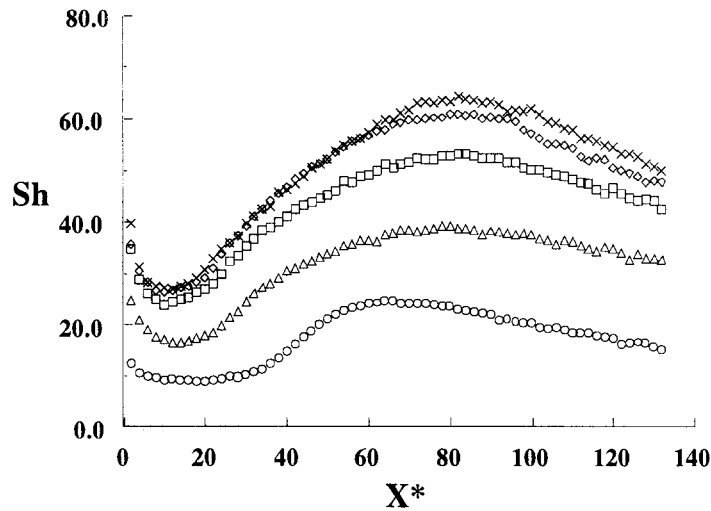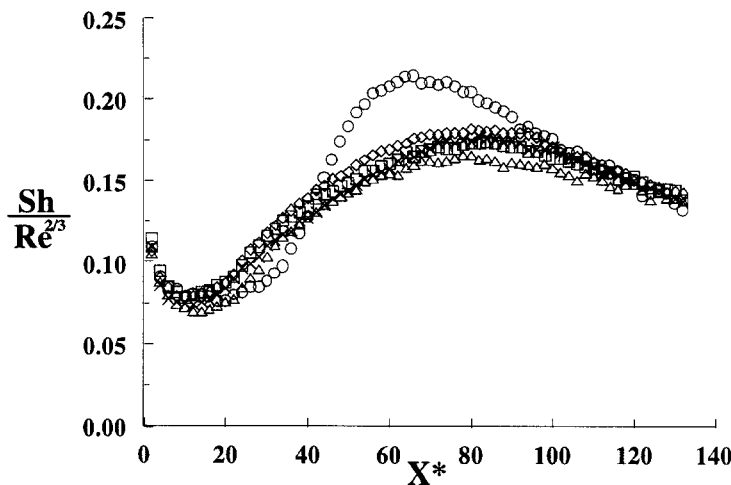
Figure 2. (a) Sherwood number (Sh) distribution *vs.* X^*: $\bigcirc$, $Re_H = 1200$; $\triangle$, $Re_H = 3700$; $\square$, $Re_H = 5400$; $\diamond$, $Re_H = 6200$; $\times$ $Re_H = 7000$; (b) replotted data of Figure 2a, by using $Sh/Re_H^{2/3}$ as ordinate

Re_H tend to coalesce into a tightly packed band. However, the data for relatively low Re_H display appreciable departure from this band.

Concluding remarks

Laboratory measurements of the spatial variations of Sh indicate the presence of a minimum and of a maximum. The minimum point of Sh is seen at a short distance X_i^* behind the leading edge. This point is shown to be associated with suppressed convective activities near the secondary separation point. The physical argument is compatible with the preceding accounts on the flow structure.

The maximum point of Sh is located in the reattachment zone. Convective activities are vigorous in this region. The effect of Re_H on the locations of the minimum- and maximum-Sh points is consistent with the picture of global flow pattern.

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