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

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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 $2720 < Re_H < 17,900$, in which $Re_H = U/H \nu$, and $\nu$ 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;

$$h_m = \frac{\rho_s (\Delta t/\Delta \tau) / \rho_{sv, w}}{P_v}$$

in which $\rho_s$ and $\rho_{sv, w}$ denote, respectively, the density of naphthalene and the naphthalene vapor concentration at the wall. Here $\Delta t$ 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;

$$Sh = h_m H / D_f$$

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

The range of $Re_H$ considered in the present experiments was $1200 < Re_H < 8000$. 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 ($250 \text{ mm} \times 250 \text{ mm}$) $U_{in}$ varied from 1.5
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, which was naphthalene-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; Ota and Kon 1974, 1980). As shown in Figure 1b, the present data satisfactorily reproduce the characteristic features of the pressure distribution with X*/H = 0.5-s stabilization period. The measurement of the 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*/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. It is notable that the Cp curves tend to become independent of ReH when ReH exceeds approximately 6000. In the lower range of ReH, the Cp curves show a mild dependence on ReH in moderate downstream regions 5.0 < X*/H < 12.0. Also, as ReH 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 ReH 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* behind the leading-edge corner (X* = 0). In the region between the leading edge and X**, the Sherwood number decreases monotonically with X*, and the rate of decrease of Sh becomes more conspicuous as ReH increases. After passing the minimum, the Sh curve increases with X* until it hits a maximum at a moderate downstream location X***. At farther downstream locations, Sh gradually decreases with X*. The rate of spatial variations of Sh tends to steepen as ReH 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

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**Notation**

- $c_p$: pressure coefficient \(\equiv (p - p_\infty) / 0.5\rho U^2\)
- $D_f$: diffusivity of naphthalene
- $H$: half thickness of the plate
- $h_m$: local mass transfer coefficient
- $Re_H$: Reynolds number \(= U_{\infty}H/\nu\)
- $Sh$: Sherwood number \(= h_{m}/D_f\)
- $\Delta t$: naphthalene sublimation thickness
- $U_{\infty}$: free-stream velocity

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

**Greek**

- $\Delta t$: exposure time
- $\nu$: kinematic viscosity
- $\rho$: density of air
- $\rho_s$: density of solid naphthalene
- $\rho_{v,\infty}$: naphthalene vapor concentration at the wall

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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 \(X^*_s\) 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 \(X^*_s\) moves upstream.

The maximum of Sh, which is seen at a moderate distance \(X^*_{r} \) 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, \(X^*_{r} \) 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 reasonable single fit when they were replotted by using Sh/Re_2H/3 as the ordinate, as displayed in Figure 2(b). Evidently, the data for high

\[ \text{Figure 2. (a) Sherwood number (Sh) distribution vs. } X^*: \bigcirc, \text{Re}_H = 1200; \triangle, \text{Re}_H = 3700; \square, \text{Re}_H = 5400; \bigcirc, \text{Re}_H = 6200; \times, \text{Re}_H = 7000; \]
\[ \text{(b) replotted data of Figure 2a, by using Sh/Re_2H/3 as ordinate} \]
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 $X^*$ 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.

References


