compared to that of the $+1$ g case. When U is 0.6 m/s, the periodic oscillation of the flame tip in $+1$ g ceases to oscillate in microgravity. On the other hand, when $U = 1.1$ m/s, the flame motion becomes nonperiodic even in the microgravity condition. These results indicate that, the $+1$ g periodic oscillating flame at $U = 0.6$ m/s is induced by the buoyancy instability, whereas the nonperiodic oscillating flame at $U = 1.1$ m/s is due to the combined effect generated by both the jet inertial force and centrifugal force. That is, under the condition of $Le > 1$, the hydrodynamic instability due to the combination of the jet inertial force and centrifugal force plays an important role in switching from the periodic mode to the nonperiodic mode.

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References

[1]Law, C. K., and Faeth, G. M., "Opportunities and Challenges of Combustion in Microgravity," *Progress in Energy and Combustion Science*, Vol. 20, 1994, pp. 65–113.

[2]Kono, M., Ito, K., Niioka, T., Kadota, T., and Sato, J., "Current State of Combustion Research in Microgravity," *Proceedings of the Combustion Institute*, Vol. 26, 1996, pp. 1189–1199.

[3]Ronney, P. D., "Understanding Combustion Processes Through Microgravity Research," *Proceedings of the Combustion Institute*, Vol. 26, 1995, pp. 2485–2506.

[4]Durox, D., Baillot, F., Scoufflaire, P., and Prud'homme, R., "Some Effects of Gravity on the Behavior of Premixed Flames," *Combustion and Flame*, Vol. 82, 1990, pp. 66–74.

[5]Kostiuk, L. W., and Cheng, R. K., "Imaging of Premixed Flames in Microgravity," *Experiments in Fluids*, Vol. 18, 1994, pp. 59–68.

[6]Koustik, L. W., and Cheng, R. K., "The Coupling of Conical Wrinkled Laminar Flames with Gravity," *Combustion and Flame*, Vol. 103, 1995, pp. 27–40.

[7]Bedat, B., and Cheng, R. K., "Effects of Buoyancy on Premixed Flame Stabilization," *Combustion and Flame*, Vol. 107, 1996, pp. 13–26.

[8]Cheng, R. K., Bedat, B., and Koustik, L. W., "Effects of Buoyancy on Lean Premixed V-Flames Part I: Laminar and Turbulent Flame Structures," *Combustion and Flame*, Vol. 116, 1999, pp. 360–375.

[9]Sinibaldi, J. O., Mueller, C. J., Tulkki, A. E., and Driscoll, J. F., "Suppression of Flame Wrinkling by Buoyancy: The Baroclinic Stabilization Mechanism," *AIAA Journal*, Vol. 36, No. 8, 1998, pp. 1432–1438.

[10]Sheu, W. J., Sohrab, S. H., and Sivashinsky, G. I., "Effect of Rotation on Bunsen Flame," *Combustion and Flame*, Vol. 79, 1990, pp. 190–198.

[11]Cha, J. M., and Sohrab, S. H., "Stabilization of Premixed Flames on Rotating Bunsen Burners," *Combustion and Flame*, Vol. 106, 1996, pp. 467–477.

[12]Ishizuka, S., "Characteristics of Tubular Flame," *Progress in Energy and Combustion Science*, Vol. 19, 1993, pp. 187–226.

[13]Sakai, Y., and Ishizuka, S., "The Phenomena of Flame Propagation in a Rotating Tube," *Proceedings of the Combustion Institute*, Vol. 26, 1996, pp. 847–853.

[14]Ueda, T., Kato, T., Matsuo, A., and Mizomoto, M., "Effect of Burner Rotation on the Flame Shape of Laminar Premixed Bunsen Flame," *2nd ASPACC on Combustion*, Australia/New Zealand, Chinese, Chinese Taipei, Japan, and Korean Secs. of the Combustion Inst., 1999, pp. 218–220.

[15]Gotoda, H., and Ueda, T., "Characteristic of Flame Tip Oscillation of a Bunsen Type Premixed Flame with Burner Rotation," *Transactions of the JSME*, Vol. 67, No. 658, 2001, pp. 1529–1535 (in Japanese).

[16]Gotoda, H., Maeda, K., Ueda, T., and Cheng, R. K., "Periodic Motion of Bunsen Flame Tip with Burner Rotation," *Combustion and Flame*, Vol. 134, 2003, pp. 67–79.

[17]Gotoda, H., and Ueda, T., "Transition from Periodic to Non-Periodic Oscillation of a Bunsen Type Premixed Flame with Burner Rotation," *Proceedings of the Combustion Institute*, Vol. 29, 2002, pp. 1503–1509.

[18]Asano, S., and Tokuo, T., "Introduction of MGLAB Drop Experiment Facilities," *Space Forum*, Vol. 6, 2000, pp. 411–416.

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Associate Editor

Vortex Shedding from Rectangular Plates

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Introduction

VORTEX excitation from rectangular elongated plates when the length parallel to the flow is much greater than the height perpendicular to the flow has been investigated experimentally by Nakamara and Nakashima[1] and Nakamura et al.[2] They concluded that vortex shedding from elongated flat plates with square leading and trailing edges is dominated by the impinging shear layer instability, when a single separated shear layer can be unstable in the presence of a sharp downstream corner.[3] Recently, Hourigan et al.[4] considered the trailing-edge shedding to be a powerful mechanism leading to self-sustained oscillations. They found that the trailing-edge shedding plays an important role in the stepwise behavior of the Strouhal number with increasing a chord-thickness ratio, which is a subject of this Note.

Discussion

Transition in vortex shedding from the von Kármán type to the impinging shear layer instability has been observed when the Reynolds number was increased from 200 to 300 (Ref. 1). Experimental data show that on short plates ($c/t < 3$, c/t being the chord-thickness ratio) the flow separates at the leading-edge corner and the shear layers interact directly, without reattaching to the plate's surface, thus, forming a regular vortex street. On longer plates ($c/t > 3$), the shear layers are reattached upstream of the trailing edge and form a separation bubble that grows and may divide, depending on the chord-thickness ratio (c/t): $m = 1$ (one bubble) for $c/t = 3$–5, $m = 2$ (two bubbles) for $c/t = 6$–8, and $m = 3$ (three bubbles) for $c/t = 9$–12. These bubbles are convected toward the trailing edge (Fig. 1). The flow patterns reveal that the leading-edge separation bubble was nearly steady. For Reynolds numbers $Re > 300$, experimental results show that the Strouhal number $Sr(c)$, based on the chord length, increases stepwise with c/t increasing from 3 to 12, namely,

$$Sr(c) = fc/U = 0.55\, m \tag{1}$$

where f and U are the vortex shedding frequency and the freestream velocity, respectively, and m is the number of vortices (bubbles).

Vortex shedding from elongated rectangular plates has been investigated numerically in Refs. 4–6. In the present Note, we used a new numerical approach, which is based on an immersed-boundary

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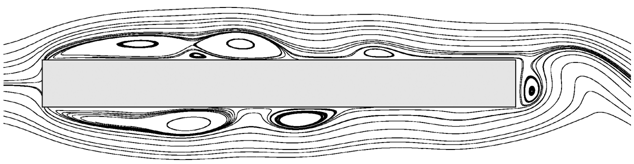

Fig. 1 Streamlines, c/t = 10, Re = 300.

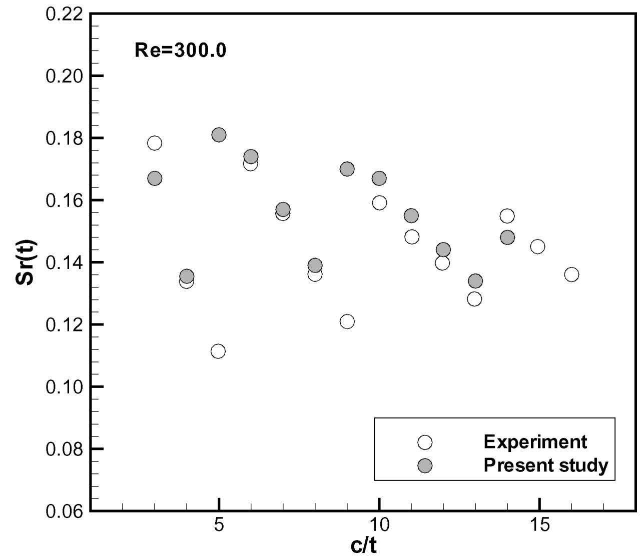

Fig. 2 Strouhal number $Sr(t)$ vs c/t, Re = 300.

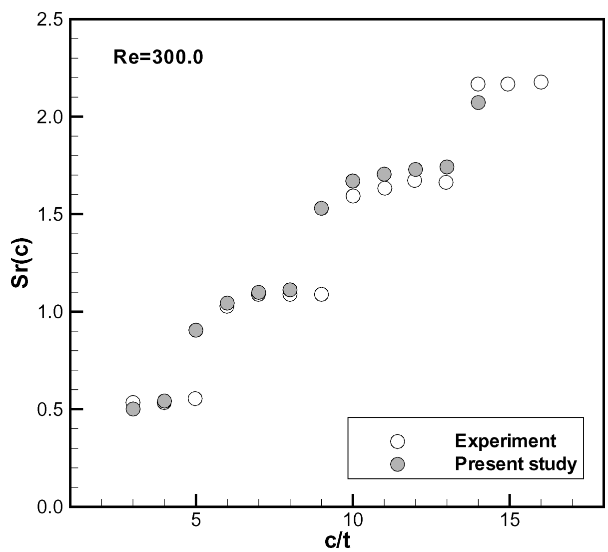

Fig. 3 Strouhal number $Sr(c)$ vs c/t, Re = 300.

method and was suggested in Ref. 7. (Details of the numerical simulations will be published elsewhere.) The flow patterns and characteristics we obtained are in good agreement with experimental findings.[1,2,5] We have performed numerical simulations of flows around rectangular plates for chord-thickness ratio varying from 3 to 12 and Reynolds numbers of 200 and 300 based on the plate's thickness. Our simulations confirm that the dominant vortex shedding frequency f gradually decreases with increasing c/t and then jumps to a higher value (Fig. 2). It is plausible to assume that the discrete jumps in frequency are related to the leading-edge separation bubble bifurcation. Figure 3 shows the experimental and computed values of the Strouhal number $Sr(c) = fc/U$, based on the chord length, vs the chord-thickness ratio c/t. The data show a stepwise increase of the Strouhal number $Sr(c)$ with increasing c/t. In Refs. 1, 2, and 5, the Strouhal number was measured at $Re = 300$–10^3. It was found that at each branch the Strouhal number is approximately constant, that is, $Sr(c) = 0.55$–0.60 m, where m is an integer and corresponds to the number of vortices formed on the plate's side. The stepwise behavior does not appear at $Re = 200$; $Sr(c)$ increases monotonically with c/t (Fig. 4). In this Note we suggest some simple considerations for explaining the trend of the Strouhal number to increase stepwise. These considerations are based on the assumption that vortex shedding has a traveling-wave nature. We assume the (nonlinear) wavelength of oscillation to be of the form

$$2\pi/\alpha = c/m \tag{2}$$

where α is the wave number and m is an integer and is not known before the full problem is solved numerically. Furthermore, we suggest that the dominant frequency f and the wave number α are connected by the traveling-wave relation

$$2\pi f = U_c\alpha \tag{3}$$

where U_c is the phase speed of the vortex shedding. Substituting Eq. (2) into Eq. (3) yields

$$fc/U = \gamma m, \qquad \gamma = U_c/U \tag{4}$$

Expression (4) is identical to Eq. (1), which was experimentally found for the Strouhal number $Sr(c)$. One can see that the coefficient in Eq. (1) can be associated with the phase velocity of vortex shedding relative to the freestream velocity γ. In our calculations, $\gamma \approx 0.55$, which is in agreement with Refs. 1, 2, and 5. The phase velocity may be approximated by the mean velocity across the leading-edge separation bubble (0.5–$0.6U$). As in previous publications on

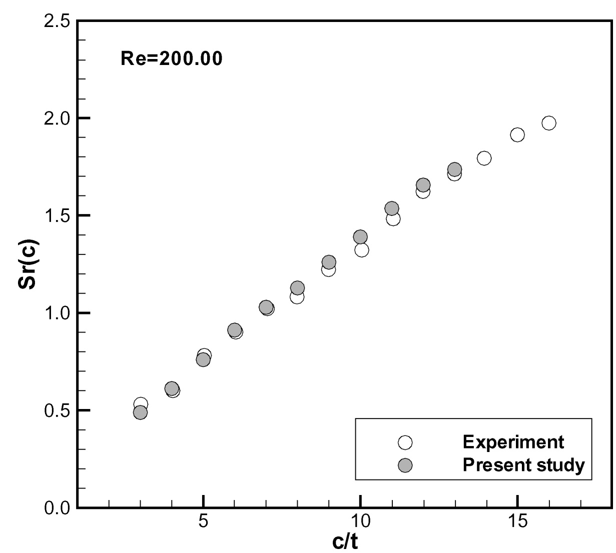

Fig. 4 Strouhal number $Sr(c)$ vs c/t, Re = 200.

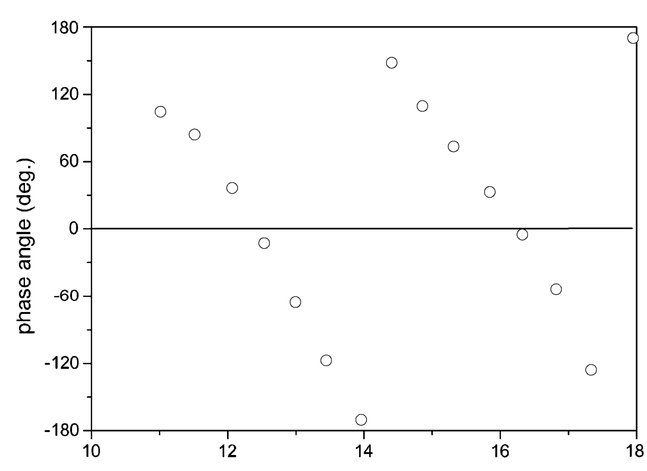

Fig. 5 Phase angle, c/t = 8, Re = 300.

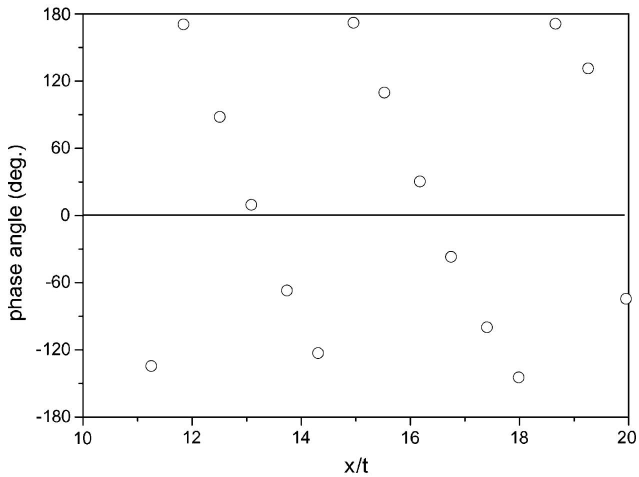

Fig. 6 Phase angle, $c/t = 10$, $Re = 300$.

vortex shedding from rectangular plates[1,2,5] m in Eq. (4) is related to the number of vortices formed on the plate's side or to the multiwave solutions of the problem. In Figs. 5 and 6 we show the phase angle ϕ of the velocity oscillations at the dominant frequency along the plate's side. The phase angle, relative to the reference point at the leading edge ($x = 0$), is computed at a distance of about $0.5t$ from the plate's side. The dominated frequency has been detected using the fast Fourier transform. We used a bandpass filter when more than one frequency exists. We found that the vortex shedding frequency in the wake is equal to the dominated frequency computed along the plate's side. The data in Figs. 5 and 6 show that $\phi = 2\pi m x / c$, which supports our travel-wave assumption (2) regarding the wavelength. The same result has been measured by Nakamura et al.[2] at Reynolds numbers $(1\text{–}3) \times 10^3$.

Conclusions

Experimental studies of vortex shedding from a rectangular elongated plate, when the cord length parallel to the flow (c) is much greater than its height (t), show that the Strouhal number $Sr(c)$ increases stepwise with c/t increasing from 3 to 12. Investigating a flow phenomenon described by a frequency f, one can consider a Strouhal number $Sr = fl/u$ as a nondimensional frequency when l and u are characteristic length and velocity, respectively. For a phenomenon considered in this Note, $l = c/m$ and $u \approx 0.5\text{–}0.6U$ are a natural choice for characteristic parameters, when m and U are the number of vortices (bubbles) formed on the plate's side and the freestream velocity, respectively. This was confirmed numerically for Reynolds numbers $Re = Ut/\nu > 300$. Assuming that vortex shedding has a traveling-wave nature, we suggest simple considerations for explaining the trend of the Strouhal number to increase stepwise.

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References

[1]Nakamura, Y., and Nakashima, M., "Vortex Excitation of Prisms with Elongated Rectangular, H and ⊢ Cross-Sections," *Journal of Fluid Mechanics*, Vol. 163, 1986, pp. 149–169.

[2]Nakamura, Y., Ohya, Y., and Tsuruta, H., "Experiments on Vortex Shedding from Flat Plates with Square Leading and Trailing Edges," *Journal of Fluid Mechanics*, Vol. 222, 1991, pp. 437–447.

[3]Rockwell, D., and Naudascher, E., "Review of Self-Sustaining Flow past Cavities," *Journal of Fluids Engineering*, Vol. 100, 1978, pp. 152–165.

[4]Hourigan, K., Thompson, M. C., and Tan, B. T., "Self-Sustained Oscillations in Flows Around Long Blunt Plates," *Journal of Fluids and Structures*, Vol. 15, 2001, pp. 387–398.

[5]Nakamura, Y., Ohya, Y., Ozono, S., and Nakayama, R., "Experimental and Numerical Analysis of Vortex Shedding from Elongated Rectangular Cylinders at Low Reynolds numbers 200–10^3," *Journal of Wind Engineering and Industrial Aerodynamics*, Vol. 65, 1996, pp. 301–308.

[6]Ohya, Y., Nakamura, Y., Ozono, S., Tsuruta, H., and Nakayama, R., "A Numerical Study of Vortex Shedding from Flat Plates with Square Leading and Trailing Edges," *Journal of Fluid Mechanics*, Vol. 236, 1991, pp. 445–460.

[7]Kim, J., Kim, D., and Choi, H., "An Immersed-Boundary Finite-Volume Method for Simulations of Flow in Complex Geometries," *Journal of Computational Physics*, Vol. 171, 2001, pp. 132–150.

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Study of Flame Structure and Soot Formation on Heptane/Air Diffusion Flame

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Introduction

HIGHER hydrocarbon fuels are extensively used in practical devices such as internal combustion engines, industrial furnaces, and powerstation gas turbines. Normal heptane (n-C_7H_{16}) is a representative higher hydrocarbon fuel. The laminar flame speed of n-heptane/air[1] and the structure of opposed flow heptane flames[2,3] have been studied experimentally and numerically. Many gaseous species, up to C_6-hydrocarbon, were measured, and the numerical results showed relatively good agreement with the measurements, except for the higher hydrocarbon species. A chemical mechanism for n-heptane oxidation and pyrolysis has been developed and validated against several independent data sets, including flow reactor experiments by Held et al.[4] A few other heptane chemical mechanisms have been also reported.[5,6] The soot formation in heptane flames has been studied by the use of global soot kinetics[7,8]; however, a global gas chemical mechanism for heptane combustion was used in this study.

The soot formation and soot radiation effects in heptane flames, especially in high-pressure flames, have not yet been studied by consideration of detailed gas chemical kinetics and full treatment of radiation heat loss. The soot and radiation effects in opposed flow methane/air diffusion flames were studied previously.[9] The radiation heat loss with both emission and absorption is considered with the exact solution of the radiation transfer equation for a nongray medium. The radiation from soot strongly affects the soot formation.

The specific objective of this Note is to study the opposed flow heptane/air diffusion flame structure, including soot formation, by the use of different detailed gas chemical mechanisms and global soot kinetics, as well as different thermal radiation models. The calculations that used different heptane mechanisms were compared with the measurements by Seiser et al.[2] for temperature and species distributions.

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