Letters to the Editor

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An Extension of the Theory of Diabatic Flow

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OUR work on two- and three-dimensional diabatic flow began in 1945 with a search both for a general formulation of the subject and a specific calculation of forces on bodies in the fields of flow. The general study was completed first and has been presented in three papers.[1] Results have also been obtained by other workers.[2–5] We can now report the calculation of diabatic forces.

On thermodynamic grounds, as we suggested in 1945, one would expect that a body immersed in a moving fluid containing a heat source would experience a force; for the fluid pressure, owing to the presence of the body, is changed in the region where the fluid is heated, and is returned to its upstream value at a point far downstream from the body.* Both general theory and a specific example indicate[1(b), (c), 4] that the effects of a heat source are much like those of a fluid source. Also on aerodynamic grounds, therefore, a heat source should produce a force since the velocity over the surface of the body is changed by the source more on the side near the source than on the far side. Similarly one can see that the force in the x direction will vary approximately as $\cos 2\theta_0$ where θ_0 gives the angular position of the source measured at the body from the direction of flow or x axis.

To these qualitative arguments we add, as typical of results that can be obtained, a specific calculation of the force on a circular cylinder. The complex potential Ψ for an incompressible, irrotational flow field that contains a cylinder Γ of radius a with center at $z=0$, a fluid source of strength m at $z=z_0=R_0 \exp i\theta_0$, and has uniform velocity in the x direction $(-V_0)$ at $+\infty$ is,[6] if there is no circulation about the cylinder,

$$\Psi=-V_0(z+a^2z^{-1})+(m/2\pi)\log(z-z_0)(a^2z^{-1}-\bar{z}_0). \tag{1}$$

If ρ is the fluid density, the complex force F_x-iF_y per unit length on the cylinder $(\rho i/2)\int_\Gamma \Psi'^2 dz$, becomes, when the integration is carried through,

$$F_x-iF_y=\rho m a^2 z_0^{-2}[V_0+(z_0 m/2\pi)(R_0^2-a^2)^{-1}]. \tag{2}$$

The terms on the right correspond to the interaction of the source with, respectively, the flow induced by the body and by the source itself. For a continuous distribution of sources of density σ in a neighborhood ΔA of z_0 the second term drops out. If also we use the known connection[1(c), 4] between the heat source strength per unit mass and time, Q, and the (effective) fluid source strength σ, we find

$$F_x-iF_y=\rho V_0(a^2R_0^{-2})(Q/c_pT_0)\Delta A \exp(-2i\theta_0), \tag{3}$$

c_pT_0 being the entropy per unit mass of the fluid before heating. The $\cos 2\theta_0$ dependence for F_x is thus confirmed. The calculation is less accurate for source positions in front of the cylinder than for other positions because the equations do not make allowance for vorticity in the wake of the source. The correct value of ρ to use in Eq. (3) depends on the relative positions of the streamline passing around the body and the heated region.

We have thus shown that a force both in and perpendicular to the direction of the flow can be produced in diabatic flow of a perfect fluid over a body. The calculation is of course applicable both to the diabatic flow and to the case of mass addition to an incompressible fluid. The classical adiabatic flow only produces forces normal to the flow and then only if there is circulation about the body. If both circulation and heat (or fluid) sources are present it can be shown that there are additional forces in both directions.

Further fundamental investigation of these diabatic forces seems warranted. The size of the computed force arising from the heating is not inconsiderable. An order of magnitude calculation shows that the force is $(2\dot{\eta}q\Delta A/V_0)$ where q is the dynamic pressure and $\dot{\eta}$ is the heating rate expressed as the fractional time rate of change of enthalpy. The corresponding result for a sphere can be obtained. Since the whole calculation is based on first-order perturbation treatment of the (non-linear) diabatic flow equations, and since a compressible fluid does not admit fluid sources of finite strength and infinitesimal extent, further extension of the theory is required when the heat source strength is not small or when compressible fluids are considered at any but the lowest Mach numbers. Some idea of the range of the validity of the perturbation treatment and of the magnitude of the compressibility corrections can be gained from references 1(c) and 4. For a realistic calculation, allowance must also be made for the departure of the fluid from the inviscid, non-turbulent model considered here.

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[1] (a) B. L. Hicks, Quart. App. Math. **6**, 221 (1948); (b) Quart. App. Math. **6**, 407 (1949); (c) Third Symposium on Combustion, Flame and Explosion Phenomena. Paper No. 25 (Williams and Wilkins).
[2] Victor P. Starr, J. Meteor. **6**, 188 (1949).
[3] George W. Platzman (private communication).
[4] H. S. Tsien and Milton Beilock (private communication).
[5] Chan-Mou Tchen, Phys. Rev. **76**, 883 (1949).
* This argument can be formalized to show that the work done on the body per second because of the fluid element Δm is nearly equal to $(R\mathbf{V}_2\cdot\nabla T_1)$ where V_2 is the velocity induced at Δm by the body and T_1 is the temperature rise of the fluid owing to the heat release at Δm.
[6] Compare Milne-Thomson, *Theoretical Hydrodynamics* (1938), Chapter VIII.

The Inelastic Scattering of Neutrons by Light Nuclei

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WE have investigated the inelastic scattering of 2.5 Mev neutrons by light nuclei. In many such elements the level spacing is so wide that only the lowest level is excited by neutrons of this energy. Thus the γ-rays produced in this process are homogeneous and this facilitates the determination of their energy and intensity. Furthermore, theoretical calculations of cross section for inelastic scattering are simplified when only a single transition to the ground-state of the scattering nucleus occurs.

The neutrons were produced by the d-d reaction using an occluded target with deuterons of 100-kev energy. Considerable care was taken to minimize scattering in the vicinity of the target which was made of $\frac{1}{3}$-mm aluminum foil, soldered to the end of an aluminum tube of $\frac{1}{4}$-mm wall thickness. This tube was waxed to the glass end of the accelerator column. In this way not more than 4.3 γ-rays/1000 neutrons originated in the target.*

Disk-shaped scatterers, 2 cm in diameter and 5 mm thick, were placed directly in contact with the target. With deuteron currents of the order of 100 μA air cooling was found to be adequate.

The γ-rays from the scatterer were detected in a pair of thin-walled glass Geiger-Müller counters set up in coincidence, using a polystyrene converter in front of the counter to produce the secondary electrons. The absolute sensitivity of this arrangement was measured with γ-rays from Co^{60} and Na^{24}. By placing aluminum foils between the two counters, the absorption curve of the secondary electrons was found. Knowledge of the form of this curve and its end-point enabled us to determine the energy and estimate the degree of homogeneity of the γ-rays.