Int. J. Heat Mass Transfer. Vol. 16, pp. 217–219. Pergamon Press 1973. Printed in Great Britain

THE USE OF AEROSOLS FOR THE VISUALIZATION OF FLOW PHENOMENA

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(*Received* 7 *July* 1972)

INTRODUCTION

MANY insights into the processes that take place in heat, mass, and momentum transfer can be obtained by the visualization of a flowing medium with injected tracers. Flow visualization in gases is usually obtained by the injection of smoke into a wind tunnel or similar flow apparatus. Several systems have recently been developed using smoke [1, 2] and a fog of kerosene [3, 4]. It is necessary to ignite and burn some material such as wood chips, straw, or tobacco in batches to generate smoke, and the smoke must then be cooled and filtered. This note describes a method of flow indicator generation that utilizes a polydisperse liquid aerosol of DOP (di(2-ethylhexyl)-phthalate* that is generated at room temperature in a system with no moving parts [6]. The particles produced are of known size and flow rate, and the system is continuously operable and controllable for several hours duration with the only requirement being a filtered and regulated supply of compressed air. The important advantages of simplicity in design and economy in construction are retained for the aerosol generator. The DOP aerosol is non-toxic and non-corrosive under normal laboratory conditions, and has the suitable properties of a high flash point and chemical inertness. This generated aerosol is especially useful in the visualization of oscillatory and turbulent flows. Photographs of the Karman vortex streets formed in the wakes of vibrating cables are presented to illustrate some recent results obtained with the system. The principle of aerosol generation for flow indicators is useful not only in basic research experimentation but also for industrial studies of ventilating ducts, filters, and sealed containment systems.

THE AEROSOL GENERATION SYSTEM

The aerosol generation and injection system used in the authors' experiments is illustrated schematically in Fig. 1. Compressed air from a laboratory supply outlet is passed through a pressure control valve and gage so that the entrance flow into the vertical inlet pipe and atomizer nozzles can be metered. The compressed air is fed through the atomizer nozzles to produce a high velocity air stream through four holes which lie at least 25 mm below the surface of the DOP liquid in the nozzle head. The exiting streams of air atomize the nearby liquid by means of high shearing action and produce an aerosol of small particles. The supply of liquid DOP into the high shear region is maintained by vertical feed holes in a collar mounted on the body of the nozzle pipe.

The atomized particles of DOP are next passed through a tubing system to a jet impactor that is designed to reduce the size range of dispersed particles in the aerosol. This impactor consists of a brass tube with a horizontal slit jet orifice at the lower end. The aerosol is passed vertically through the slit and undergoes stagnation flow on a small horizontal plate. Many of the large particles are stripped from the mixture, and the particle size spectrum is reduced. The design and construction of the atomizer nozzle and jet impactor are well founded and simple, and are described in a related NRL report [6]. This work was carried out in order to produce aerosols of known particle size distribution and mass concentration for the testing of high efficiency filters. The authors' apparatus is comparable in design to the system described in this latter publication except that all dimensions exclusive of the atomizer and impactor pipe diameters are reduced by one half. The experiments of Echols and Young [6] showed that the average size of aerosol particles was 0·69 μ after passing through a system similar to that of the present study with an inlet air pressure of 25 psig ($1{\cdot}76 \times 10^{-2}$ kg/mm^2). The particle size distribution was such that most particles were less than 1·3 μ dia. after passing through the jet impactor under the conditions just mentioned. The aerosol is fed into a flexible pipe or tube, and is ready for introduction into a wind tunnel or experimental apparatus.

The generation and injection systems for the DOP aerosol thus have the advantages of no moving parts and no need for ignition, combustion, and cooling of the tracer. Further, it is possible to generate a flow indicator with a predictable particle size range and mass concentration. Precautions should be taken to guard against the clogging of the atomizer nozzle and jet impactor with contaminants in unfiltered compressed air.

FLOW VISUALIZATION USING AN AEROSOL

The effectiveness of a DOP aerosol for flow visualization is demonstrated by photographs of the von Kármán vortex street formed in the wake of a vibrating cable. The wind tunnel and related measurement systems have been described in detail elsewhere [7, 8]. An aerosol is introduced

* See reference [5] for detailed information on the physical properties of DOP.

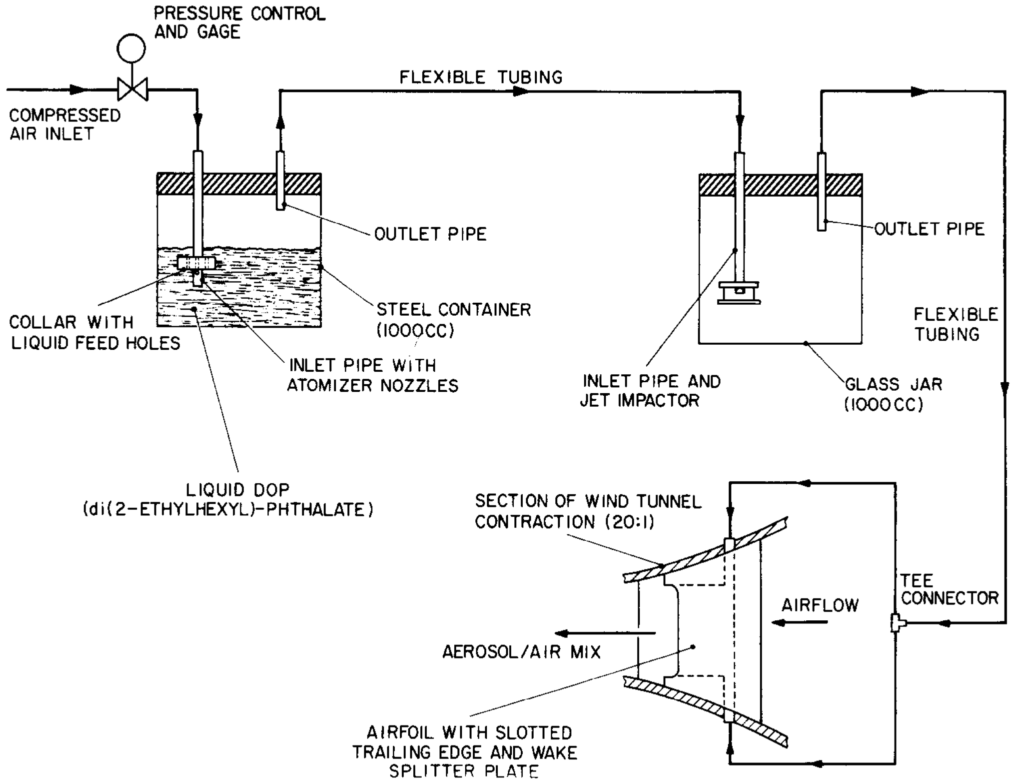

FIG. 1. Schematic layout of an aerosol generation and injection system for flow visualization.

into the tunnel through the slender airfoil with slotted trailing edge and splitter plate shown in Fig. 2. This airfoil is mounted vertically in the tunnel contraction section in a region of favorable pressure gradient as shown schematically in Fig. 1. A mixture of DOP and air from the aerosol generator is fed through the airfoil slots to form a stable sheet of indicator at the exit of the contraction section. Two hot wire probes are placed in the exit section, one outside the airfoil wake and the other downstream of the splitter plate, so that the aerosol bleed rate can be adjusted to correct the wake deficit. A uniform velocity profile, flat within one per cent over the exit cross section, was obtained in this way. Any number of alternate injection systems might be designed for use with the aerosol generator described in the previous section.

The aerosol injection system was used in a flow visualization study of the vortex wake behind vibrating smooth cylinders and stranded cables at Reynolds numbers between 120 and 350. An example is shown in Fig. 3. The photograph was taken with the flow "frozen" by a strobe and time delay synchronized with the output of the shaker used to vibrate the cable. This photograph shows the vortex wake formed behind a cable transversely vibrating in a uniform crossflow in the regime where the vibration and vortex shedding frequencies lock together, or synchronize, and control the shedding [7, 8]. Several characteristics of the vortex shedding from stranded cables in this regime have been reported in the literature [9]. The model is vibrating at 110 per cent of the Strouhal frequency and 30 per cent of a diameter for a flow Reynolds number of 220. The wake in Fig. 3 represents an instantaneous visualization of the vortex street when a vortex is forming downstream of the lower shoulder of the cable in this part of the shedding cycle. The wake of a vibrating cylinder or cable comprises the three classical flow regimes of the Kármán vortex street—the formation, stable, and unstable regions [10]—at Reynolds numbers below 350. The flow in the vibrating cylinder wake for the frequency-locked flow regime at these Reynolds numbers is discussed in detail elsewhere [2, 7, 11].

The photograph in Fig. 3 is representative of a large number recently taken by the authors and gives ample evidence of the results that can be obtained using a liquid aerosol as an indicator for the visualization of oscillatory and turbulent fluid flows.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the support of the Ocean Technology and Acoustics Divisions of the Naval

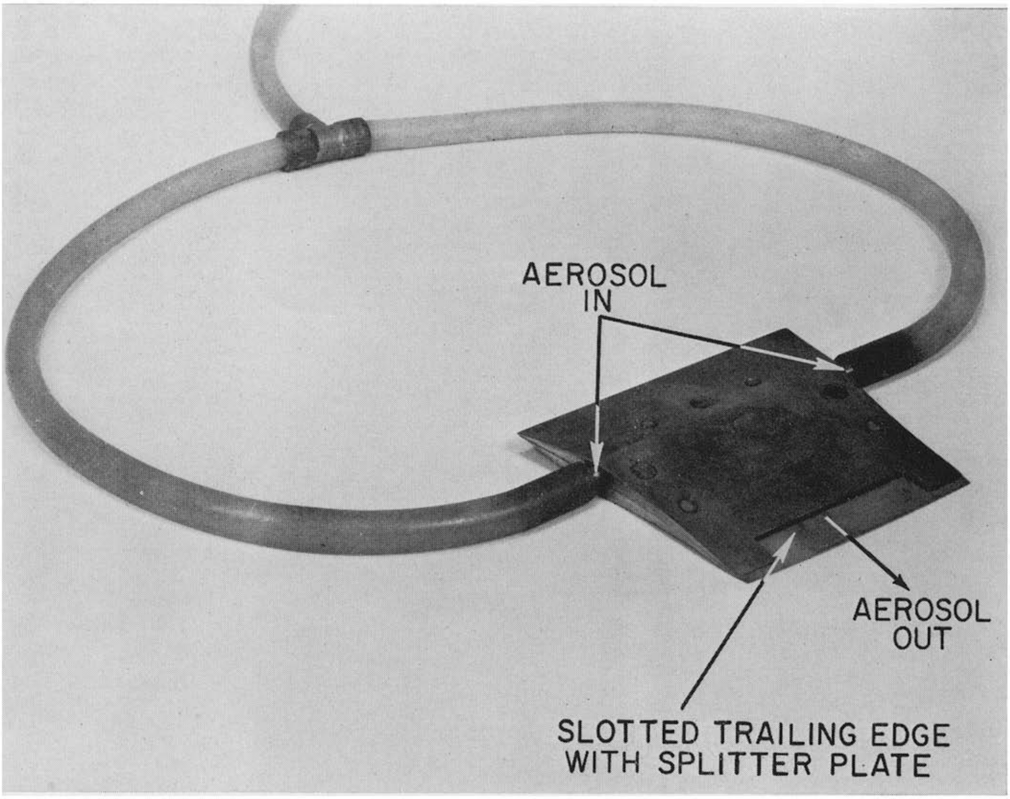

FIG. 2. The slender airfoil with slotted trailing edge and wake splitter plate used to inject a DOP (di(2-ethyl-hexyl)-phthalate) aerosol into the wind tunnel.

FIG. 3. Flow visualization of vortex shedding from a vibrating six-stranded cable. The Reynolds number based on cable outer diameter and free stream speed is 220. The vibration frequency is 110 per cent of the Strouhal frequency for this Reynolds number and the amplitude is 30 per cent of a diameter.

H.M.

Research Laboratory for the work reported in this paper. R. A. Moyle capably designed the jet impactor and several atomizer nozzles used in the aerosol generator described herein.

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Int. J. Heat Mass Transfer. Vol. 16, pp. 219–223. Pergamon Press 1973. Printed in Great Britain

MELTING HEAT TRANSFER WITH WATER JET

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(*Received* 3 *May* 1972 *and in revised form* 3 *August* 1972)

NOMENCLATURE

d, nozzle diameter [cm];
D, diameter of the cavity [cm];
g, gravitational constant [980 cm/s^2];
h, heat transfer coefficient [cal/cm^{2}s°C];
k, thermal conductivity of water [cal/cms°C];
M, melting flux [g/cm^{2}s];
Nu, Nusselt number (hd/k);
Pr, Prandtl number $(C_p\mu/k)$;
Re, Reynolds number $(dV\rho/\mu)$;
s, thickness of the ice block [cm];
T_w, water jet temperature [°C];
T_i, ice temperature [°C];
v, average water jet velocity [cm/s];
V_0, nozzle water jet velocity [cm/s];
W, melting rate [g/s];
z, distance between nozzle tip and the initial ice surface [cm];
λ_f, latent heat of fusion [cal/g];
μ, viscosity of water [g/cms];
ρ, density of water [g/cm^3];
ρ_i, density of ice [g/cm^3].

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INTRODUCTION

The application of high speed water jets in the mining and excavating industry is being realized as an effective and economical means for tunneling. The jets have the advantage that there are no parts in direct contact with the medium, thus preventing tool wear, and no change of equipment is necessary when going from soft to hard formations [1–3]. However, application of water jets to excavate frozen medium needs further considerations of heat-transfer characteristics of the medium. Due to the complex nature of the system, not much theoretical treatment has been given to the jet