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AN EXPERIMENTAL SET-UP FOR INTERACTION TURBULENCE–CHEMICAL REACTION RESEARCH

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NOMENCLATURE

A,	constant;
E_{11},	one-dimensional spectrum;
f,	frequency;
K,	cell constant [cm^{-1}];
K_1,	one-dimensional wave number;
L_f,	integral scale of turbulent field;
M,	mesh size of the grid;
R,	electrolyte resistance;
R_λ,	turbulent Reynolds number;
r,	correlation space;
$\bar{U}$,	mean velocity in X-direction;
$\bar{U}_c$,	center line mean velocity $\bar{U}$;
u',	root mean square of u.
u,	component of velocity fluctuation in X-direction;
V_K,	Kolmogorov velocity scale;
X,	distance from grid;
X_0,	virtual origin.

Greek symbols

ε,	viscous dissipation rate;
Γ,	specific conductivity of the solution;
ν,	kinematic velocity;
λ_f,	Taylor microscale of turbulent field;
η_K,	Kolmogorov length scale;
τ_K,	Kolmogorov time scale.

1. INTRODUCTION

A NEW EXPERIMENTAL set-up which permits study of the interaction between turbulence and chemical reaction is described and its main turbulence characteristics are reported. The turbulent Reynolds number is large enough to permit a detailed analysis of the mechanisms which prevail in fine grained turbulent structures. Investigations are aimed to obtain typical information useful for modelling methods of turbulent flows in a reactive environment. Indeed, most of the closure methods which succeed when only dynamic characteristics of flows are concerned fail when chemical reactions play an important role [1, 2].

It is therefore most important to carry out fundamental experiments in connection with elementary configurations which permit the systematic analysis of each of the relevant parameters. The experimental device described below was designed in order to examine the influence of turbulence on the chemical reaction rate in a water flow which is made weakly reactive and the eventual molecular effects on fine turbulence structures [3].

The fundamental criterion of such a study is the Damkhöler number defined as the ratio of the time scale of the chemical kinetic reaction and the time scale of the turbulent diffusion process. In experimental situations characterized by large Dankhöler numbers the chemical reaction is completely controlled by chemical kinetic; on the contrary, for small Damkhöler numbers the turbulent diffusion process becomes a leading parameter. In this work the Damkhöler number has been chosen in a particular range (0.01–10) in order to make possible the investigation of the respective role of these two phenomena.

In addition, it is convenient to minimize the variations of the physical properties of the fluid and an isothermal reaction in aqueous phase has been chosen. These reasons lead us to choose for the reaction the alkaline hydrolysis of methyl formiate.

2. EXPERIMENTAL FACILITIES

The hydrodynamical characteristics of the experimental set-up is a compromise between conflicting requirements. The Reynolds number has to be large enough and the experimental parameters adjustable in a large range, but the overall size of the water tunnel and the requisite power have to be limited.

The dimensions of the test section were fixed to permit comparisons with the turbulence data available in a similar experimental set-up with passive flows [4]. Moreover, the turbulent structures have to develop without being strained by the external wall, which determine the overall size of the testing chamber.

The experimental set-up [Figs. 1(a) and (b)] is essentially made of a primary and a secondary circuit.

2.1. *The principal circuit*

The principal circuit consists of:

two coaxial containers 7 and 5 m^3 in volume, made of P.V.C. and used as storage and suction tanks, respectively;

a butterfly gate;

a centrifugal pump with adjustable rotating speed. It can provide a maximum flow rate of 200 m^3/h under a pressure head of 0.35 bar. Under discharge a control of the pressure head insures that the flow rate is constant in the test sections. A dilute NaOH solution (0.4 $\mathrm{g/dm}^3$–4 $\mathrm{g/dm}^3$) is handled by this circuit;

a settling chamber with fine meshed screens and a contraction.

the turbulence-generating grid with a square mesh size equal to $M = 3$ cm (distance between rod centre lines). It consists of two plans of round rods with six rods in each plan. This grid is also used to inject an average flow rate of 5 $\mathrm{g/dm}^3$ of methyl formiate by means of 276 injectors. Its solidity (projected solid area per unit total area) is about 34%;

a test section of 2 m in long and 300 mm in diameter. It is made of Plexiglass and hold a probe support which permits transverse step-by-step displacements (1/10 mm). This system can be set up from place to place in the flow direction (20 cm).

2.2. *The secondary circuit (or injection circuit)*

The secondary circuit (or injection circuit) is composed of:

a storage tank 2.5 m^3 in volume, it contains a diluted solution of methyl formiate;

a pump providing a maximum flow rate of 20 m^3/h under a pressure head of 2.5 bar;

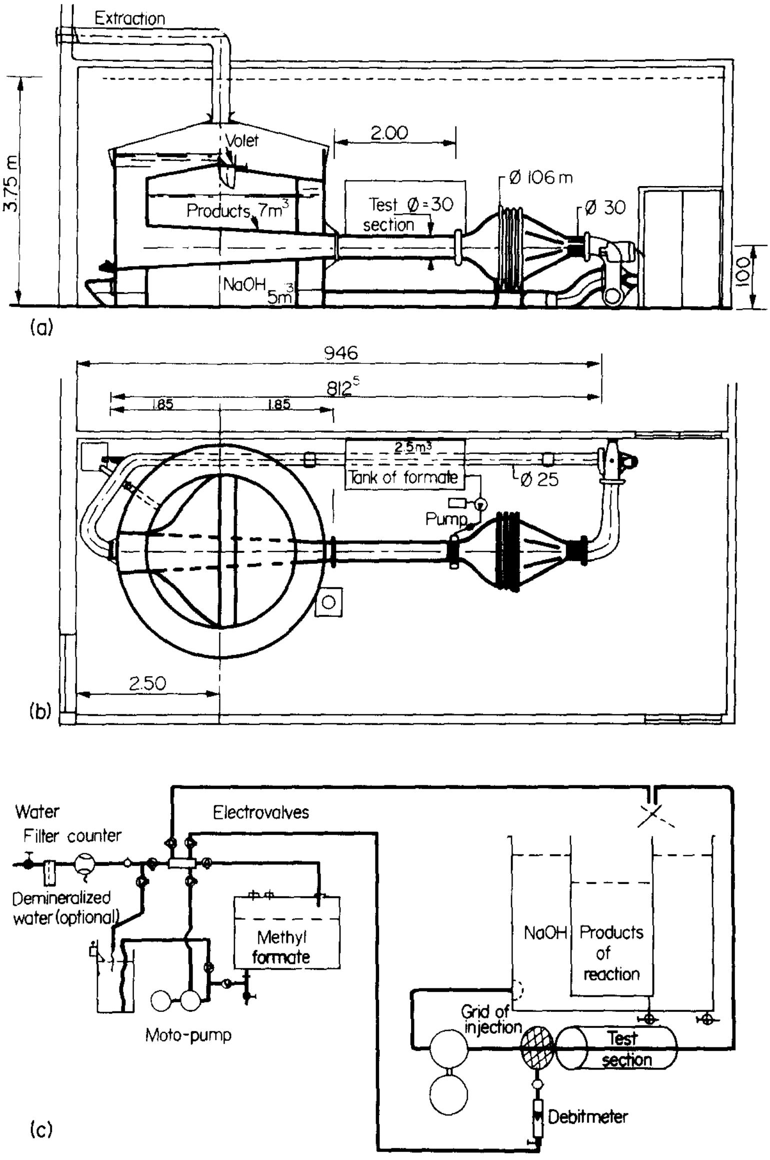

Fig. 1. (a) and (b) General rig layout. (c) Flow diagram of injection and dilution system.

a dilution device for sodium hydroxide and formiate controlled pneumatically. [Fig. 1(c).]

3. MEASUREMENT EQUIPMENT AND PROCEDURE

3.1. *Concentration fluctuation measurements*

The conductivity method [5] was chosen for the measurement of concentration fluctuations of chemical species. The probes were similar to those described by Gibson and Schwartz [6] and by Torrest and Ranz [7]. They consist of a fine platinum wire, which is quartz coated to eliminate the effect of electrochemical reactions. The sharp-headed form of such probes permits almost local measurements of the instantaneous concentration. These conductivity probes are characterized by the constant $K = R\Gamma$ (R and Γ are the resistance of the electrolyte and the specific conductivity of the solution, respectively). In this experiment K was about $100\,\text{cm}^{-1}$ which made it possible to explore up to $2 \times 10^{-6}\,\text{cm}^3$ in volume.

3.2. *Velocity fluctuation measurements*

Conical film probes (Thermosystems type 1230 W) or wedge shaped probes (Thermosystems type 1241-20 W) were used for the instantaneous measurements of one or two velocity components.

The signals delivered by the probes are statistically sampled and numerically treated through an acquisition-computer system.

4. EXPERIMENTAL RESULTS

In order to determine the hydrodynamical field at the working station, measurements of the mean and turbulent velocities distributions were performed with a pure water flow. In spite of the boundary layer contamination the mean velocity did not differ from the maximum velocity by more than 1% over about 80% of the test section (Fig. 2).

The longitudinal turbulent level u'/U was measured at several sections from $X/M = 12$ to $X/M = 50$. At $X/M = 12$, u'/U was about equal to 8% and was approximately constant over almost 80% of the section (Fig. 2). This large value of u'/U was probably linked to the great thickness of the grid in

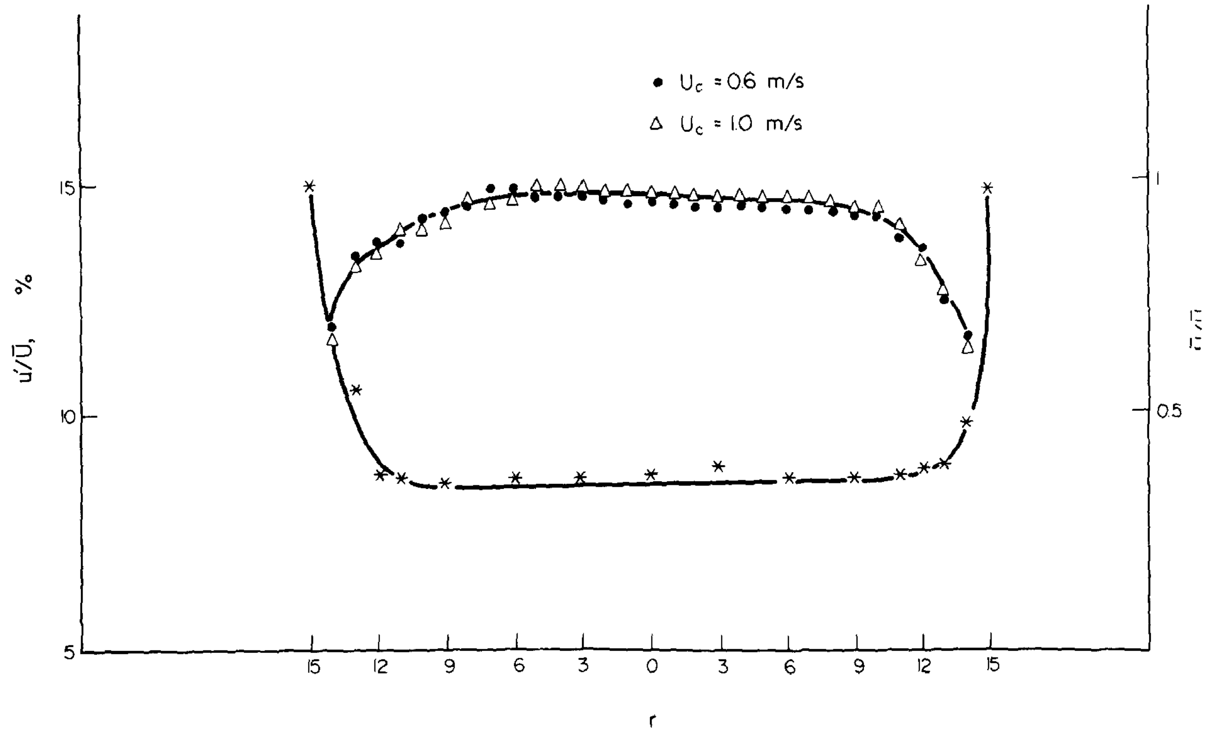

FIG. 2. Average velocity profile at $X/M = 12$ and turbulent intensity profile at $X/M = 12$, $\bar{U} = 0.6$ m/s.

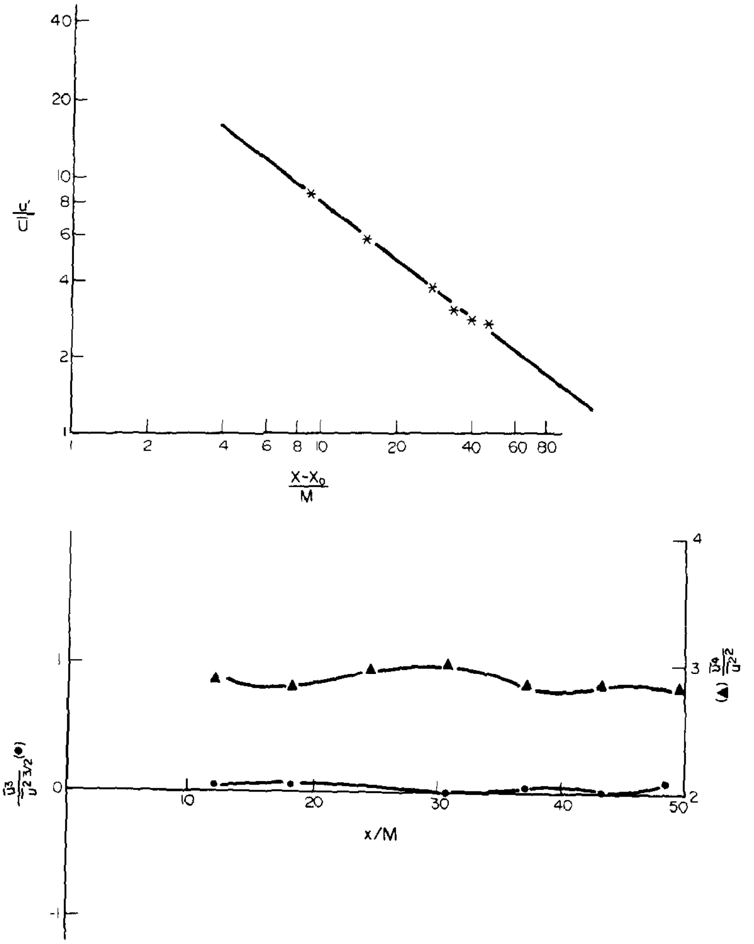

FIG. 3. (a) Decay of turbulent intensity behind grid, $\bar{U} = 0.6$ m/s, $R_M = 30000$. (b) Skewness factor and flatness factor in terms of X/M.

the flow direction ($\simeq 5$ cm). The decay rate of u'/U with X/M was well represented by a power law

$$\frac{u'}{\bar{U}} = A\left(\frac{X - X_0}{M}\right)^{-0.75}$$

which is in good agreement with experimental data reported by Gibson and Schwartz [6] [Fig. 3(a)].

The skewness and flatness factors of the longitudinal component of the velocity fluctuation were approximately those of a Gaussian distribution [Fig. 3(b)]. Only accounting for statistical kinematic properties of turbulent fields is it usually found that they are not far from a normal law, but chemical reactions can introduce a large departure from a Gaussian law when concentration fluctuations of chemical species are considered. The one-dimensional spectra $E_{11}(k)$ of $\overline{u_1^2}$ are given [Fig. 4(a)]. They are defined by

$$E_{11}(K_1) = \frac{1}{2\pi}\int_0^{+\infty} \overline{uu'(r)}\cos(K_1 r)\,\mathrm{d}r$$

where K_1 is the wave number component in the flow direction.

Over an important range of K_1 an inertial range is observed, i.e. $E_{11}(K_1) \sim K_1^{-5/3}$. In the frequency domain this corresponds to the interval 10–10^2 Hz.

Viscous effects can be emphasized by plotting $K_1^2 E_{11}(K_1)/\bar{u}^2$ vs K_1 [Fig. 4(b)]. They become relevant for large values of K_1, i.e. $N \geqslant 10^3$ Hz.

Other turbulent characteristics can be obtained from the spectral analysis:

the dissipation rate

$$\bar{\varepsilon} = 30\nu \int_0^{\infty} K_1^2 E_{11}(K_1)\,\mathrm{d}K_1$$

where ν denotes the kinematic viscosity;

the longitudinal integral scale

$$L_f = \frac{\pi}{\bar{u}^2} E_{11}(0) = \frac{\bar{U}}{2}\,\frac{\tilde{E}_{11}(0)}{\bar{u}^2}$$

by use of an extrapolated value of $E_{11}(K_1)$ for $K_1 \to 0$;

the longitudinal Taylor scale

$$\lambda_f^2 = 30\,\nu\frac{\bar{u}^2}{\bar{\varepsilon}};$$

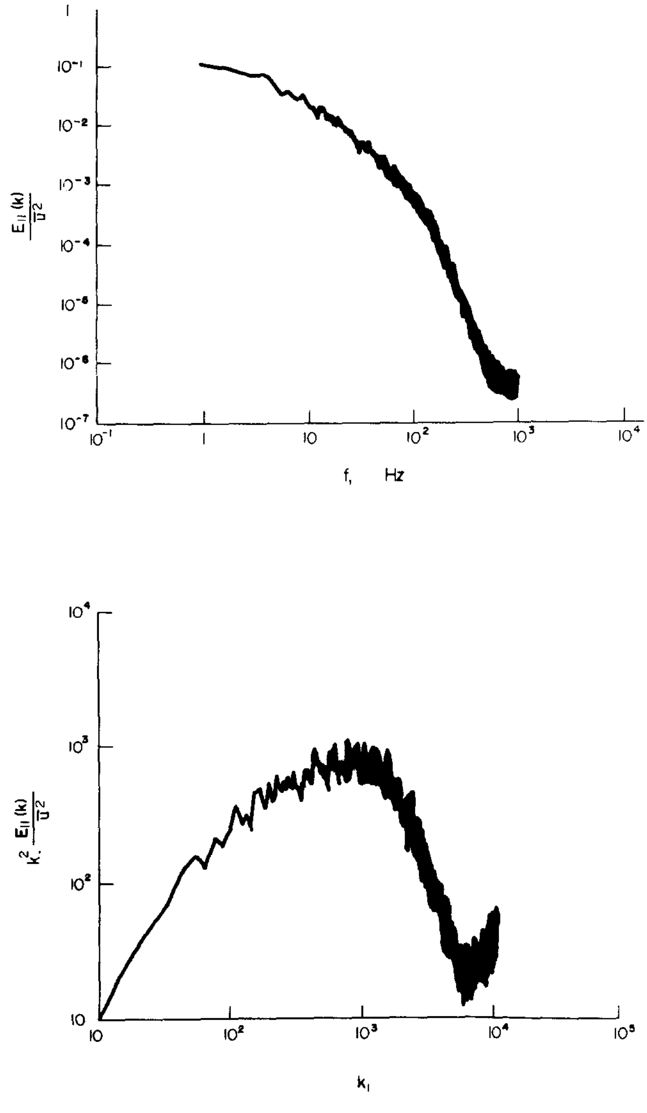

FIG. 4. (a) The normalized spectrum of the kinetic energy $E_{11}(K)/\overline{U^2}$ at $X/M = 12$, $\bar{U} = 0.6$ m/s. (b) The dissipation spectrum $K^2[E_{11}(K)/\overline{u^2}]$ at $X/M = 12$, $\bar{U} = 0.6$ m/s.

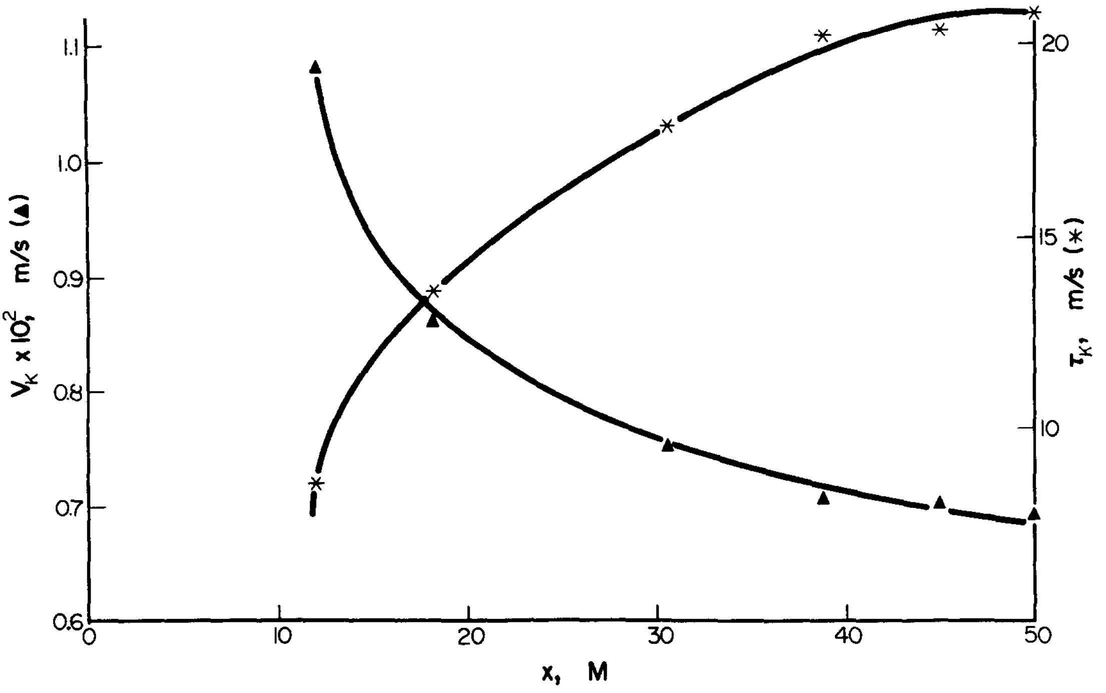

FIG. 5. Kolmogorov's velocity scale V_K and Kolomogorov's time scale τ_K in teams of X/M.

the Kolmogorov scales (Fig. 5)

$$\eta_K = \left(\frac{\nu^3}{\bar{\varepsilon}}\right)^{1/4}, \quad v_K = (\nu\bar{\varepsilon})^{1/4}, \quad \tau_K = \left(\frac{\nu}{\bar{\varepsilon}}\right)^{1/2}.$$

At $X/M = 12$ we obtained: $L_f \simeq 3$ cm, $\lambda_f \simeq 1.7$ mm so that the turbulent Reynolds number $R_\lambda = u'\lambda_f/\nu$ is of order 100, and the time scale of the energetic structures, defined by u'/L_f is of the order of 1.6 s.

These first results show that the experimental set-up is adequate for further turbulent investigations. In particular the introduction of a chemical reaction with a controlled rate will be undertaken in the near future.

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