Pergamon

Ann. occup Hyg Vol 39, No. 2, pp 211–221, 1995
Elsevier Science Ltd

0003–4878/95 $9.50+0.00

0003–4878(94)00112-X

A REVIEW OF WAKE EFFECTS ON WORKER EXPOSURE

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(*Received* 9 *August* 1994)

Abstract—Boundary layer separation leads to the formation of a wake region downstream of a worker in an air flow field. This fundamental phenomenon is responsible in many cases for compromising the intended beneficial effect of ventilation designed to reduce worker exposure to toxic airborne substances. A review of some simple mathematical models to describe the impact of wakes on exposure is presented along with some field studies illustrating the effect. The importance of flow visualization to detect and correct the problem cannot be overstated. The research suggests that work practices in many cases are as important as the ventilation design in achieving successful control, and that a well designed local exhaust system must include an understanding of how the worker performs the job

INTRODUCTION

As air flows around the human body boundary layer separation produces a wake similar to that which exists behind a ship moving through the water. This is an important factor in determining a worker's exposure to toxic airborne contaminants, particularly when the source of pollution and the breathing zone are within the wake region. The wake is a mixing zone characterized by eddies or vortices which entrain air into a reverse-flow region near the body. It is this entrained air flow and the contaminant generation rate that determine worker exposure. Unlike the wake behind a ship, a clearly visible phenomenon, vortices produced around people and objects in the work environment are not observed unless flow visualization techniques are employed.

Control of worker exposure to airborne pollutants is the primary responsibility of the occupational hygienist. An understanding of how wakes impact on exposure is essential if successful control interventions are to be implemented. Exposure is typically defined as the time-weighted average concentration (C_{TWA}) experienced by the worker over some specified period (T),

$$C_{TWA} = \frac{1}{T}\int_0^T C_{bz}\,dt, \tag{1}$$

where C_{bz} is the breathing zone concentration. The period is often either 8 h or 15 min depending upon whether the occupational exposure level (OEL), selected as a target, is a short-term ceiling value or a full-shift level. The breathing zone concentration is a function of the contaminant generation rate (G) and the air velocity field (U). All

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human exposure problems to airborne contaminants may be cast within this framework: the difficulties lie in specifying G and U as functions of space and time.

The purpose of this paper is to summarize basic theoretical, experimental and field studies which have been conducted by the authors and which examine the influence of wakes on human exposure. The emphasis is on formulating a basic conceptual and mathematical model for understanding wakes and contaminant transport within them, and examining real world exposure problems in the light of the models and their limitations.

THEORY

As air flows around an object such as the human body the region immediately adjacent to it is called the boundary layer, precise definitions and a thorough discussion of which may be found in the seminal text *Boundary Layer Theory* (Schlichting, 1949). The boundary layer is a very thin region in which frictional forces are extremely important. If, as air in the boundary layer moves around the body, it encounters an adverse pressure gradient (increasing pressure in the direction of flow) it will separate from the surface and form eddies or vortices, which constitute the beginnings of the wake: various authors have described this phenomenon with reference to air flow around people (Ljungqvist, 1979; George *et al.*, 1990; Kim and Flynn, 1991a).

Boundary layer separation is classically illustrated by observing flow in the plane perpendicular to the long axis of circular cylinder with diameter (D) immersed in a unidirectional freestream of constant velocity (U). This two-dimensional approach reveals that as with so many fluid phenomenon the Reynolds number (Re), is a critical variable. At relatively low values of Re (e.g. 50–5000) a regular pattern of vortices is observed being shed downstream from alternate sides of the cylinder: this is known as a Karman vortex street. The frequency (f) with which a vortex is shed from one side of the cylinder is given by a dimensionless parameter called the Strouhal number (S) where:

$$\mathrm{S} = \frac{fD}{U}. \tag{2}$$

The value of S is very nearly constant at 0.21 over the range $500 < \mathrm{Re} < 200\,000$ although the eddies began to degrade somewhat from the laminar Karman vortex street arrangement at $\mathrm{Re} > 5000$.

Wakes around three-dimensional objects such as people are complex flows which represent a challenge both experimentally and theoretically. A tractable approach based on the simple cylinder example above was taken in George *et al.* (1990), and Kim and Flynn (1991a,b); a stationary worker is modelled as a circular cylinder of finite height (H) and diameter (D). This cylinder (worker) is assumed to be immersed in a unidirectional freestream of constant velocity (U). In addition, a point source positioned in the wake issues neutrally buoyant tracer gas at a volume flow rate (G). If separation is to occur the flow G must be small relative to that entrained by the eddies.

This approach allowed development of a model to predict the average concentration in the wake region. The model assumes that pure air is entrained into the wake at a flow Q_V where:

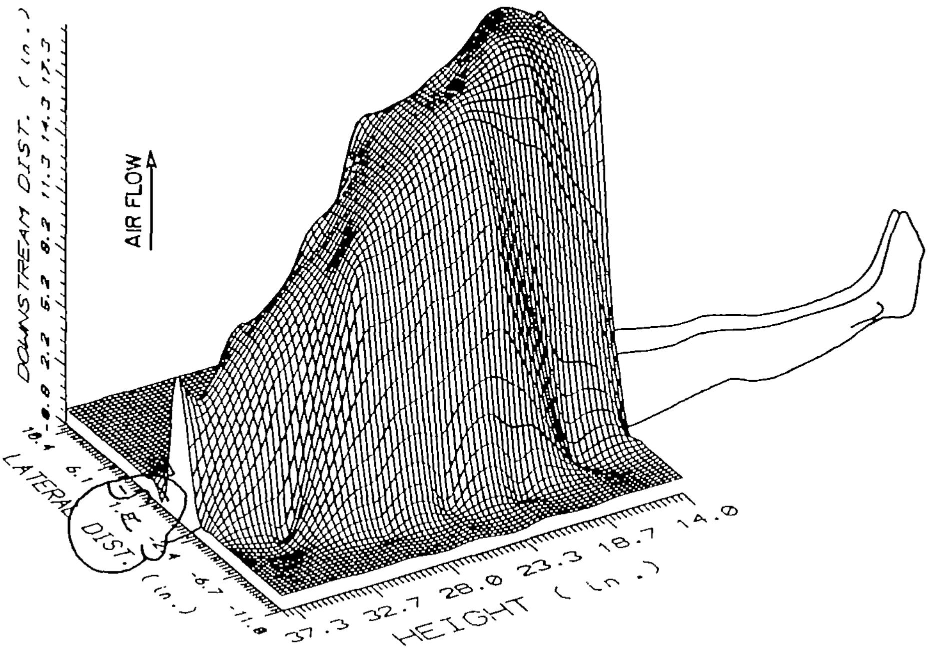


Fig 1. Reverse flow region downstream of the body determined with smoke wire techniques in wind tunnel studies using a mannequin (Kim and Flynn, 1991a).

$$Q_V = 2fV_V \tag{3}$$

and V_V is the volume of an eddy assumed to be a circular cylinder of height H and diameter D. The concentration measured in the wake region at equilibrium is calculated as:

$$C = \frac{G}{Q_V} \tag{4}$$

or

$$C = \frac{19G}{\pi UHD}. \tag{5}$$

This conceptual model is purely theoretical and based on several assumptions which were examined in laboratory wind tunnel simulations using a mannequin and air velocities designed to give Reynolds numbers representative of industrial air flows around people. In Kim and Flynn (1991a) the presence of the eddies and confirmation of the Strouhal number were documented with flow visualization and hot-film anemometry. In addition a near wake region was defined demarcating a reverse flow zone near the body (see Fig. 1). This region is assumed to be the volume over which Equation (5) applies. Further refinements to the model were presented in Kim and Flynn (1991b) which took into account empirical estimates of the eddy size, and also the three-dimensional nature of the air-flow. These three-dimensional flow patterns are illustrated in Fig. 2.

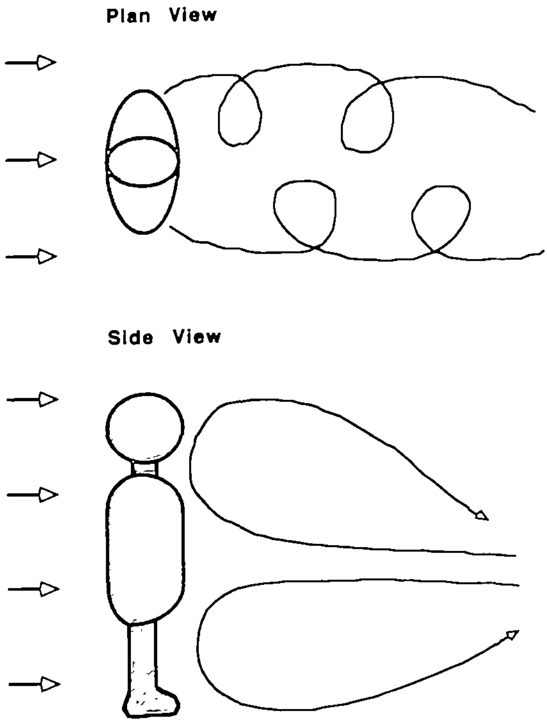


Fig. 2. Air flow structure around body, showing vortex shedding in the plan view, and counter rotating eddies in the vertical plane (Kim and Flynn, 1991a).

In George *et al.* (1990) the effect of source position within the wake on breathing zone concentration was investigated, and the orientation of the mannequin with respect to the airflow was studied. A peak in breathing zone concentration was observed when the source was in the mannequin's hands, and a dramatic reduction in exposure was observed when the mannequin was positioned to the side (see Fig. 3). In Kim and Flynn (1991b) a summary equation was presented for estimating breathing zone concentration:

$$C_{bz} = \frac{8.62G}{UHD}. \tag{6}$$

Further studies examined: (1) the influence of source momentum and direction in a simulated spray booth situation (Kim and Flynn, 1992); (2) the effect of worker position on exposure in local exhaust of arc welding (Tum Suden *et al.*, 1990); and (3) the relationship of exposure variability and boundary layer separation (Flynn and George, 1991).

In Flynn and Miller (1991) a two-dimensional numerical solution of the Navier–Stokes equations using the discrete vortex method was presented for flow around an elliptical cylinder representing a worker. This solution demonstrated that vortex shedding at the correct Strouhal number could be simulated numerically and that computational fluid dynamic tools offer a potentially valuable method for estimating worker exposure and the implications of contemplated ventilation designs

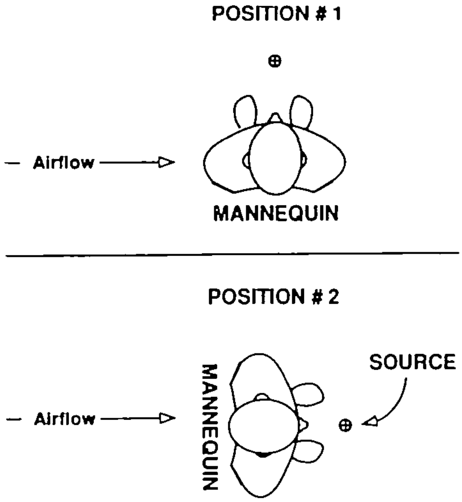


Fig. 3. Mannequin orientations with respect to air flow direction and source from George *et al.* (1990); tracer studies showed the superiority of position 1 in reducing exposures.

and work practices. A sample output from the programme showing the velocity field around the worker and the characteristic eddies is shown in Fig. 4.

The essential concept in understanding the wake effect is the generation of the spinning eddies which can result in a reverse flow region and transport of contaminant to the breathing zone. The steady, unidirectional and constant velocity freestream is transformed into a periodic swirling wake downstream of the body. If a source of pollutant and the breathing zone are within the wake exposure problems can be expected, particularly for hand-held or proximal sources.

FACTUAL SITUATIONS

With flow visualization methods it is easy to demonstrate that the wake effect is capable of destroying the intended beneficial effect of the ventilation system (Ljungqvist, 1979, 1987). Figure 5 shows, with the aid of smoke in a parallel flow and an air velocity of 0.2 m s^{-1}, that the person gives rise to a transport of impurities which, to a large extent, is directed to the respiratory organs. The smoke configuration in Fig. 5 shows similarity with the drawing in Fig. 2 because the smoke emission is at the height of the upper part of the body. Of course the configuration of the body and convection flows may also play a role in determining air patterns and exposure.

A common protective device in a laboratory is a fume cupboard, and a complex flow pattern can arise here, influenced by both the position of the cupboard sash and the movements of the person working at the cupboard. Pollutants in the fume cupboard can be discharged outward through the opening and may be inhaled by the person working there or by others in the area. Such discharge can be caused by periodic or unstable vortices or by large scale turbulence in an unstable wake region in front of the operator. These outward discharges have been visualized by using smoke tests in the presence of a person and are described in the literature (Harvey, 1979; Hughes, 1980; Ljungqvist, 1987).

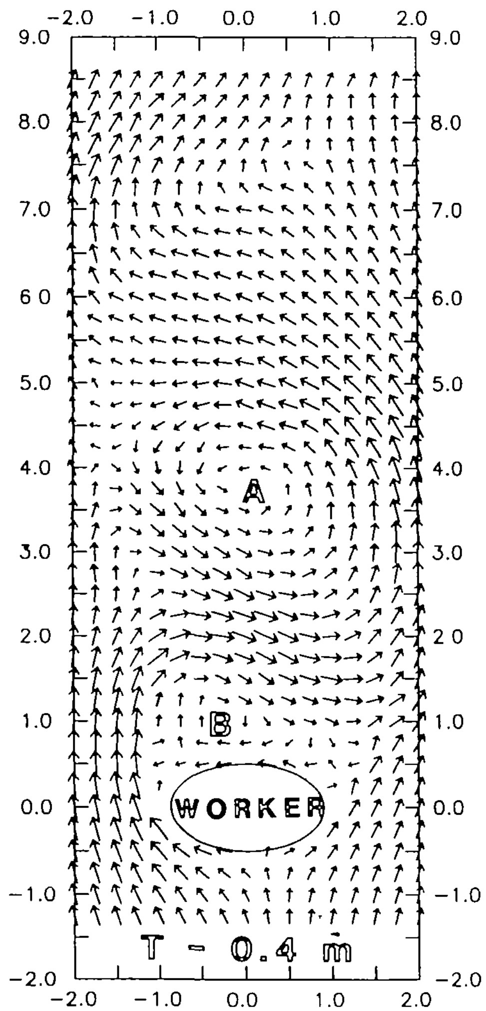
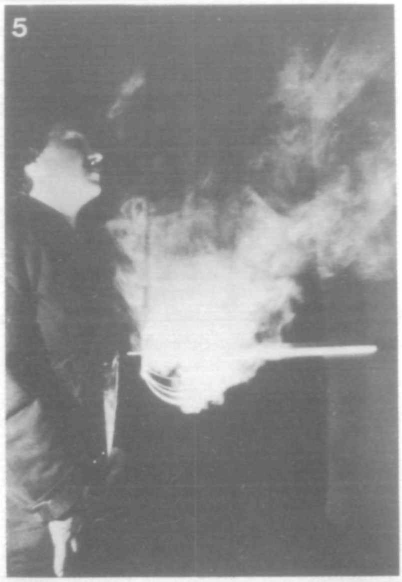


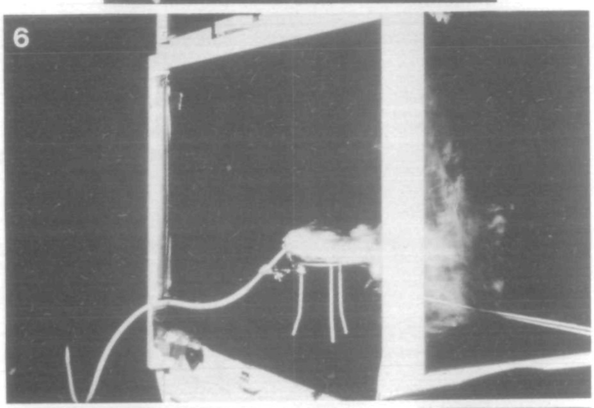
Fig. 4 Numerical prediction of the instantaneous velocity field downstream of an elliptic cylinder representing a worker 0 4 min after the start of motion, note counter rotating eddies centered at A and B (Flynn and Miller, 1991).

Figure 6 illustrates a characteristic smoke dispersal process without the presence of an operator, at a fume cupboard with well-rounded inlet edges. Figure 7 shows the dramatic change that can occur when an operator stands in front of the fume cupboard. The airflow is the standard 500 m^3 h^{-1} per m of opening (in this case 600 m^3 h^{-1} total air flow) and the sash is two-thirds open giving a mean face velocity of 0.25 m s^{-1}.

Quantitative tracer gas measurements show that outward discharge takes place even at the smallest possible openings as soon as a person uses the fume cupboard (Ljungqvist, 1991). It can be said approximately that by reducing the sash from a position two-thirds open to one that is only one-third open, discharge is reduced by 90%.

In a hospital laboratory, ventilation air is supplied to the room through supply





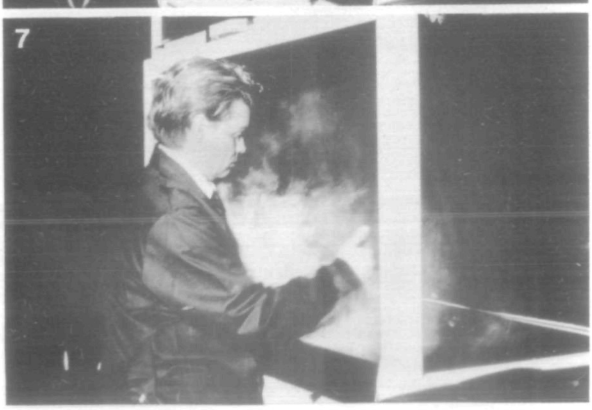
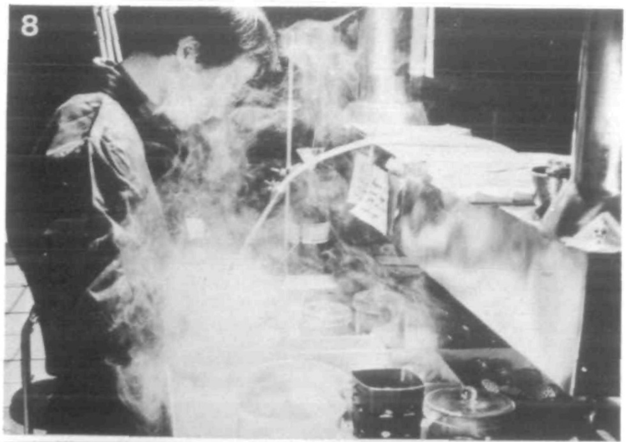


Fig. 5. Dispersion of smoke in a unidirectional air flow with a person placed in front of the smoke emission (Ljungqvist, 1979).

Fig. 6. Dispersion of smoke in a fume cupboard with two-thirds sash opening in an undisturbed flow field at a standard air flow rate of 600 $m^3 h^{-1}$ (Ljungqvist, 1987).

Fig. 7. Dispersion of smoke in a fume cupboard with two-thirds sash opening when an operator is at work. The exhaust air flow rate is 600 $m^3 h^{-1}$ (Ljungqvist, 1987).



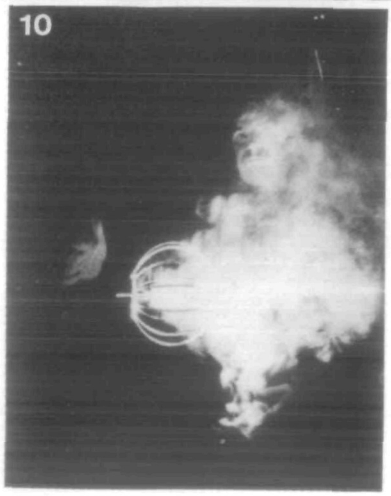


Fig. 8. Dispersion of smoke at a ventilated work station in the presence of an operator creating an unstable wake region. The exhaust air flow rate is 300 $m^3\ h^{-1}$.

Fig. 9. Dispersion of smoke in the presence of an operator when using a down-draught perforated plate, at an exhaust air flow rate of 300 $m^3\ h^{-1}$ (same workplace as in Fig. 8).

Fig. 10. Dispersion of smoke in a unidirectional air flow with a person placed at the side of the smoke emission, hand in motion (Ljungqvist, 1979).

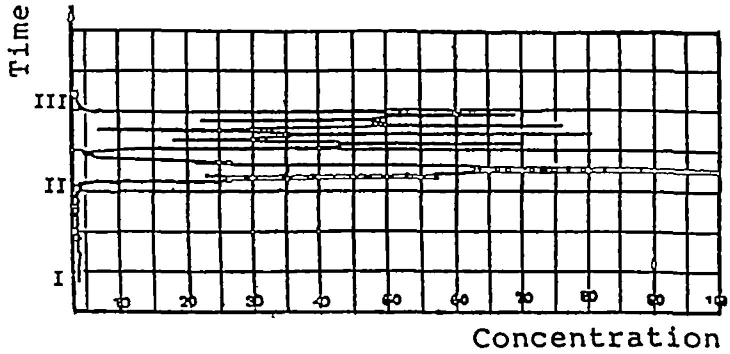


Fig. 11. Characteristic leakage properties of a fume cupboard with an operator at rest (I–II) and moving (II–III). The sash being in the upper position (Ljungqvist, 1991).

grills which create disordered conditions. The air from the room is exhausted through a horizontal ventilation duct adjacent to the work place and visible in Fig. 8. In this instance the flow has a horizontal component which gives rise to an unstable wake region and results in pollution being transported to the worker's breathing zone. The horizontal component and hence the wake region is eliminated by replacing the exhaust air duct with a horizontal perforated plate over the table to remove the pollutant via the shortest route, see Fig. 9. Ljungqvist (1992) has described the risks associated with ventilated work stations characterized by the creation of a principally vertical flow field by extracting through a horizontal perforated plate, i.e. a down-draught bench. A distinction needs to be made for hot and cold work. Good protection is possible in a situation without any heat sources which can give rise to pronounced vertical, thermal flows.

DISCUSSION

Although there is support for the simple theoretical treatment presented above, real-world exposure problems differ significantly from the models above. The models assume: (1) a stationary worker; (2) a constant velocity unidirectional free stream; (3) unobstructed near wake regions, i.e. no object downstream of the worker; and (4) a point source with constant generation rate and low momentum. In actual exposure situations these assumptions are rarely met, and a discussion of the effect of these perturbations to the basic model is appropriate.

Figure 10 (Ljungqvist, 1979) illustrates the effect of worker hand motion. Vortices from the motion of the upstream hand result in smoke dispersing into the breathing zone. A similar effect can easily appear at a fume cupboard when the operator is carrying out completely normal work. This effect is demonstrated in Fig. 11 (Ljungqvist, 1991), which plots leakage from a fume cupboard as a function of time for an operator at rest (I–II) and in motion (II–III) when the sash is in the upper position. The measuring probe is located adjacent to the chest of the operator. Figure 11 shows that when the operator is moving the leakage results in violently pulsating emissions.

In Kim and Flynn (1992) a preliminary investigation of contaminant source momentum, the presence of a downstream object and worker motion were examined using a jet of dilute sulphur hexafluoride tracer in a spray booth. The work indicated the overwhelming importance of source momentum in overcoming the effect of the reverse flow. In addition, many sources will have buoyancy due to thermal gradients and this too will result in contaminant movement not treated in the simple models above.

The assumption of a unidirectional constant velocity freestream is often not realized in real world applications. Air flow into local exhaust hoods is accelerating and may significantly reduce the tendency for vortex formation although much work needs to be done in this area. In general factors that tend to minimize boundary layer separation, i.e. the addition of flow into the near wake, or acceleration on the downstream side of the object will tend to reduce the wake effect.

CONCLUSIONS

Vortices created by a person are of two kinds, periodic or unstable. The periodic wake region is formed when a stationary person is positioned in a uniform freestream. The unstable situation is in most cases caused by motion, particularly of the hands and arms. Such vortices have limited duration, they are formed, decay, die out and are formed again and so on. In this case the frequency need not be constant but may vary.

The leakage concentration measurements from a fume cupboard in Fig. 11 show clearly the violent pulsating emissions when the operator is moving (II–III). The values recorded depend very much on the response time of the measuring equipment. This means that the values of the concentration peaks measured may depend on both how the operator moves and the analyser used. The operator's safety cannot be evaluated solely on the basis of an inflow air velocity to a ventilated workplace. The operator's position and movements, as well as other objects, will impact on the flow pattern and transport of contaminants.

In conclusion flow visualization methods can give valuable information on air movements and contamination risks. It can also be an effective tool for educating workers as to exposure risks and for training employees in effective work practices.

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