TURBULENCE IN GAS-PARTICLE FLOW

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ABSTRACT

The research of turbulence in gas-particle flows is reviewed from the historical viewpoint. Recent topics of calculations and experiments are also described.

INTRODUCTION

The subject of turbulence in gas-particle flow yields two research areas; one is particle dispersion caused by fluid turbulence and the other is modification of fluid turbulence caused by particles. These two phenomena are related closely to each other but research of them have taken different courses. While the study of the turbulent dispersion has a long history dating back to the pioneering work by G. I. Taylor(1922), it is not so long since direct evidence of turbulence modification was obtained.

TURBULENT DISPERSION

Taylor made his research of turbulent dispersion for the purpose of analyzing the effects of a smoke screen. His theory is simple and sophisticated. He deduced the diffusion coefficient. However, the diffusion coefficient given by him is based on the Lagrangian correlations while flow descriptions in ordinary fluid mechanics are usually based on the Eulerian velocities which are given as functions of space coordinates. Therefore, to apply the Taylor's theory to practical problems described by the Eulerian frame, it is necessary to know the relation between the Lagrangian and Eulerian properties. This relation has not been found on purely theoretical grounds even today. Study of this relation has been imposed to researches after Taylor. It is found experimentally that the Lagrangian correlations and the Eulerian correlations are coincident if the separations in time and space are made non-dimensional by using appropriate integral scales (Snyder and Lumley, 1971).

It was after the World War II that calculation of particle motion in a turbulent flow has been made extensively. In those calculations, the Basset-Boussinesq-Oseen equation (BBO equation) or its simplified equation (Langevin equation) has been used. Usually, motion of a single particle was considered in the calculation, and therefore it was assumed that the particle does not affect fluid motion. Calculation based on such assumption is called "one-way" now. In such cases, the problem is how to solve motion of the particle under a given fluid velocity field. The BBO equation is a linear and ordinary differential equation and thus its treatment is mathematically easier than the NS equation. As a result, theoretical approaches in turbulent dispersion have advanced fast compared with turbulence modification. Some researchers were interested in particle response to instantaneous turbulent motion of fluid. They used the Fourier analysis to obtain the frequency response of particle to fluid turbulence. These theories are described in detail in the monographs by Hinze(1959) and Soo(1967, 1990). The results of such works are useful even today for checking frequency response of tracer particles used for a laser doppler velocimetry.

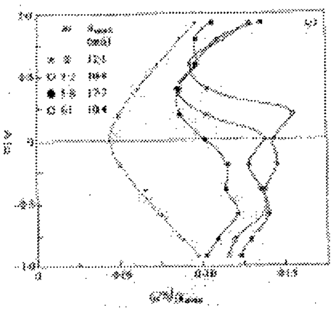
Numerical integration of the BBO equation is straightforward if the turbulent flow field is properly given and therefore the number of numerical simulations dealing with trajectories of many particles has increases since the middle of 1970's. They calculated particle trajectories by assuming instantaneous fluid velocities. Until 1980's, the turbulent field was given empirically or semi-empirically in those simulations. For example, see Yuu (1978). Now, instantaneous turbulent fluid motion can be obtained by direct integration of the NS equation. As the result, detailed structures of turbulence are unveiled. Apart from particle dispersion, some researcher are interested in heterogeneity in particle concentration caused by turbulent vortices. This subject is described in the later section.

TURBULENVE MODIFICATION

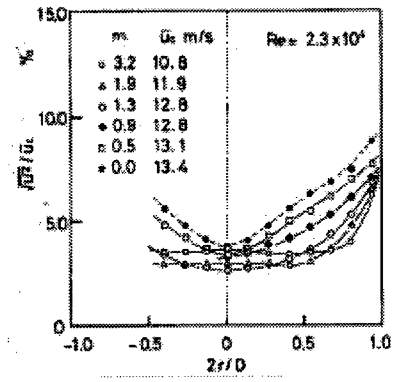
As for the turbulence modification, most of results came from experiments. This is natural because rigid theories are still difficult even for single phase turbulence. Moreover, it was not until 1970's that direct measurements of turbulence in the presence of particles were obtained. The majority of experiments have been done after early 1980's. Although measurements of turbulence modification are relatively new, interest in this phenomenon is not so new. Researchers and engineers in some engineering fields were aware of the fact that the presence of particles changes the rates of heat transfer and chemical reaction which can not be explained unless the fluid turbulence is modified by particles. The drag reduction phenomenon observed in pipe flows with small concentration of solids is another example showing indirectly the turbulence modification. These evidences were known in 1950's. Some experimental workers used a tracer diffusion technique to investigate the effect of particles on fluid turbulence. Torobin and Gauvin (1961) gave an extensive review of work before 1950's.

As is well known, the delay in obtaining the data of fluid turbulence in the presence of particles is due to the difficulties in measurements. In this respect, contribution of the laser doppler velocimetry(LDV) is enormous to the study of turbulence in multiphase flows, just as contribution of the hot wire anemometer to turbulence of single phase flows. Before invention of LDV, the hot wire or hot film velocimetry was the only means to get direct information of fluid turbulence. Although a hot-wire probe can not be used for a flow field including solid particles, a conical probe coated with a hot-film is durable to some extent in solid-liquid flows even when subjected to bombardment by solids. Therefore experimental results of turbulence in the presence of particles were obtained in the relatively early days by researchers in civil engineering who were engaged in such experiments in connection with sediment transport. In mechanical engineering, this problem has been studied in connection with an atomized fuel injection nozzle. Hetsroni and Sokolov(1971) used a hot wire probe in a gas-droplet jet and showed that particles (droplets) decrease turbulence intensity uniformly. Small liquid droplets in a gas can be regarded to have essentially the same effect as solid particles on the gas phase. They showed also that the particles decrease the spectral components of fluid turbulence at high frequency. Measurement of spectrum of fluid turbulence is still a challenging subject in fluid-solid multiphase flows.

Once LDV was available, reports on fluid turbulence in fluid-solid flows drastically increased. Various kinds of particle-laden flows including pipe flows, channel flows, free-jets, confined jets, impinging jets, boundary layers and isotropic turbulent flows have been measured so far. In these experiments, small tracer particles which are given artificially or naturally are seeded for detecting the fluid velocities. In order to obtain fluid turbulence in the presence of large particles consisting of a multiphase flow, the signal of the tracer particles must be discriminated. Before PDV (phase Doppler velocimetry) was developed, researchers were forced to develop by themselves signal discrimination devices, because commercially available LDV systems were not equipped with such signal discriminators.



(a) horizontal pipe flow (Tsuji et al. 1982)



(b) vertical pipe flow (Tsuji et al. 1984)

Fig.1 Turbulent intensities of gas phase in gas-particle two phase flow

Intensities and visibilities of scattering light were used for the signal discrimination. In such days, several research groups such as Maeda of Keio, Durst of Erlangen and Tsuji of Osaka tried to measure fluid turbulence in the presence of particles. Fig. 1 shows results obtained by the present author and co-workers(Tsuji et a., 1982, Tsuji et al. 1984).

Nowadays PDV becomes a standard equipment in multiphase flow laboratories, and precise data are obtained easier. Recently, Fritsching and Gillandt(2001) showed detailed data of turbulent energy spectra in gas-particle jet. In 1990's, PIV (Particle Image Velocimetry) became a powerful means of multiphase flow measurements. The most advantageous point of PIV is that it provides instantaneous velocity data over a plane in the flow. Simultaneous measurements of three dimensional structure of turbulence are possible by stereoscopic and holographic PIV. As examples of PIV use for particle-laden flows, see Sato et al. (1995), Khalitov & Longmire (1999), Kiger & Pan (2000) and Paris & Eaton (2001).

Two papers which summarize measured results of turbulence modification were published in the same year 1989. One is a paper by Gore & Crowe(1989) and the other by Hetsroni(1989). Authors of these papers are interested under which conditions the fluid turbulence is suppressed or enhanced by particles. Gore and Crowe(1989) re-arranged the data using the length scale ratio dp/le, where dp is particle diameter and le is a turbulent length scale. See Fig. 2.

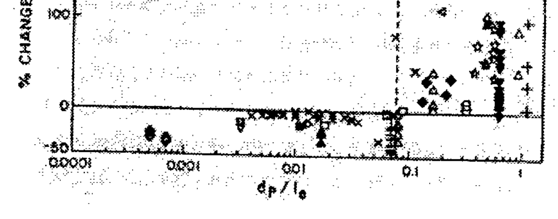


Fig. 2 Change in turbulent intensity vs. ratio of length scales (Gore and Crowe 1989)

As the length scale le, the integral length scale or the characteristic length of the most energetic eddy is used. Gore and Crowe(1989) collected the data from not only fluid-solid flows but liquid-gas flows. Their finding is that the ratio dp/le = 0.1 provides an estimate of whether the fluid(carrier phase) turbulence is increased or decreased by the particles(second phase).

On the other hand, Hetsroni(1989) tried to explain the enhenced turbulence by the vortex shedding phenomenon and therefore paid an attention to the particle Reynolds number(based on elative velocity and particle diameter). He reached the conclusion that the presence of particles with a low Reynolds number tends to suppress the fluid turbulence and particles with high particle Reynolds number tend to increase the turbulence.

Eaton (1995) summarized the data obtained in his laboratory: boundary layer (Rogers and Eaton, 1991), channel flow (Kulick at al., 1994) and backward-facing step (Fessler and Eaton, 1995). He described that the turbulence modification is a function of both the particle Stokes number and Reynolds number as well as the flow type. At the same time, he pointed out that there is not a single model which explains the existing data appropriately. His group of Stanford has been continuing to provide detailed data of turbulence modification.

THEORIES AND MODELS OF TURBULENCE MODIFICATION

Before 1970, intensive investigation of the turbulence modification was made in civil engineering. At first, they investigated mean quantities of velocity and concentration, and were interested in whether the Karman constant is affected by the presence of particles. With experimental data of turbulence at hand which were obtained using hot film probes, theories of turbulence modification like Hino(1963) were presented. On the other hand, some theoretical workers were interested in flow instability affected by suspending particles. For example, Saffman(1962) examined the stability of particle-laden gas flows based on a modified Orr-Sommerfeld equation. Velocity fluctuation in laminar flows is different from turbulence in many respects but the effects of particles on the stability is expected to have a connection with turbulence modification. Theoretical results indicate that particles stabilize and de-stabilize the laminar flows, respectively depending on conditions of concentration and particle relaxation time. Yang et al.(1990) investigated stability of gas-solid mixing layer(free shear layer) based on a modified Rayleigh equation.. They found that the presence of particles decreases the amplification rate; the particles stabilizing the flow. More recently, Wen, F. and Evans, J. (1994). Wen, F. and Evans, J. (1996). Tong, X.-L. and Wang, L.-P. (1999) and Narayanan, et al. (2001) have made the same kind of stability analysis.

In 1970's, theoretical workers like Baw and Peskin(1971) and Al Taweel and Landau(1977) attempted to construct a theory based on spectral analysis for the fluid turbulence in particle-laden flows. Their analytical work is regarded as an extension of the statistical theory of isotropic and homogeneous turbulence.

Apart from such mathematical approaches for an idealized turbulence field, there have been continued demands for predicting particle-laden flows in industrial fields. A solid fuel rocket engine is an example which triggered the studies of prediction methods. At first, fluid turbulence was not considered but as the time went on, effects of turbulence has been taken into account. Corresponding to the increase of measured results, the number of computational work has increased. Such calculations of particle-laden flows have been made intensively after early 1980's, just as experimental works of turbulence modification were made since then. Most works reflect the era of computer, i.e., a computer with high performance is a precondition for work. It is also considered that numerical calculation techniques developed for the single-phase flows have given a great impact to the field of multiphase flows.

Therefore, studies of turbulence in multiphase flows follows the same line as in the single phase flows. At first, average quantities of turbulence were dealt with. Thus, mathematical models of turbulence have been developed in the following order: simple mixing-length type zero-equation models, one-equation models and k-e type two-equation models. After LES (Large Eddy Simulation) was developed in the single phase flow, instantaneous motion of fluid has been dealt with in the multiphase flows. For details of these numerical modelings, see the reference of Crowe et al. (1997) All these models contain some factors which should be determined empirically. To get lid of such empirical aspects, DNS has been developed in single phase flow turbulence. The most advanced DNS approach in multiphase flows is to calculate flow around moving particles or bubbles by using only the NS equation. Forces acting on particles are obtained by integrating normal and tangential stresses on the surface of particles. Thus, empirical coefficients associated with drag and lift forces are not necessary in this method. Drag and lift coefficients described in text books and monographs are valid when the particle is fixed in the space where the fluid moves at the relative velocity of fluid and particle. Actually the instantaneous motion of a moving particle is affected by the flow which the particle itself produces. A typical example of this case is the particle motion affected by the vortex behind the particle. Fig.3 shows an example of such calculation. This approach is rapidly developing in the last 10 years. More recently, the Lattice-Boltzmann simulation (Qi, 2000, Cate et al., 2001) has been applied to multiphase flows. See Fig. 4.

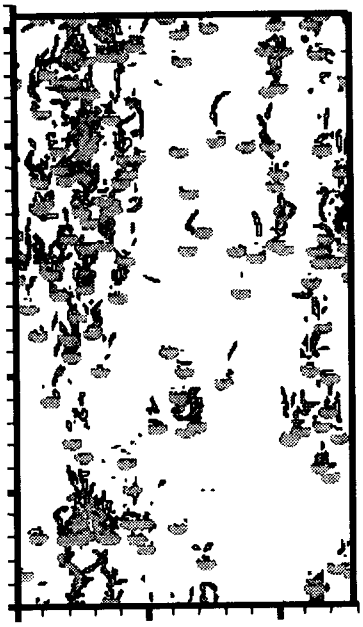


Fig. 3 Snapshot of flow field and falling particles (Kajishima and Takiguchi 2002)

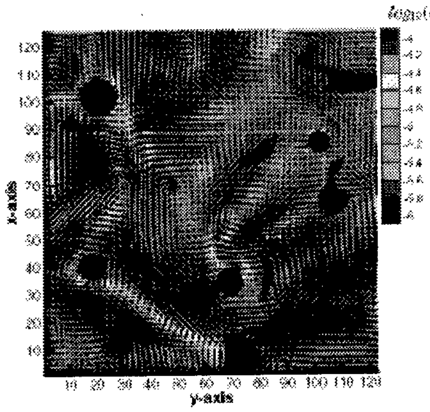


Fig. 4 Snapshot of turbulent flow field and particles (Cate et al., 2001)

HETEROGENEITY IN PARTICLE CONCENTRATION

As research tools in calculation and experimental methods are developing, turbulence structures of multiphase flows have begun to be studied in detail. What some researchers are interested in is the relation between heterogeneity in particle concentration and turbulence. The heterogeneity in particle concentration is caused by the following two factors.

(1) Interaction between particle motion and vortex field

(2) Inter-particle collision

The first case has been investigated in various flow fields such as free shear flows(Crowe et al., 1988 , Hardalupas and Horender, 2001), homogeneous turbulence (Wang and Maxey, 1993, Squire and Eaton ,1991, Eaton and Fessler, 1994, Février et al.2001) and wall turbulence (Rashidi et al., 1990, Kajishima and Takiguchi, 2002, Pan and Banerjee ,1997, Hagiwara et al. 2001). This kind of heterogeneity in particle concentration is called preferential concentration by researchers. Squires and Eaton (1991) showed that particles collect preferentially in regions of low vorticity and high strain rate. Fig.5 (Février et al.2001) is an example of preferential concentration where it is found that particles accumulate in the peripheries of large vortices.

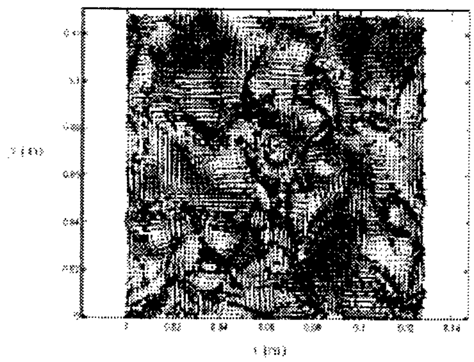


Fig. 5 Preferential concentration (Février et al.2001)

Kajishima and Takiguchi (2002) showed that particles are captured in the wake of front particles and this interaction leads to accumulation of particles as shown in Fig.3. Rashidi et al. (1990) showed that particles accumulate in the low speed streaks of fluid near the wall. Kajishima et al. (2001) investigated the relation between vortex shedding from individual particles and bursting phenomenon.

The second case has been studied by the present author's group. The idea of this approach originated from astrophysics research of asteroids. It was a puzzle why an asteroid forms such a clear ring. A theory insisted that small stars are collected by repeating inelastic collision. Goldhirsch and Zanetti (1993) made a numerical simulation where particles repeat inelastic collision under the condition without gravity and fluid. Fig. 6 shows their result in which configuration of particle clusters is observed.

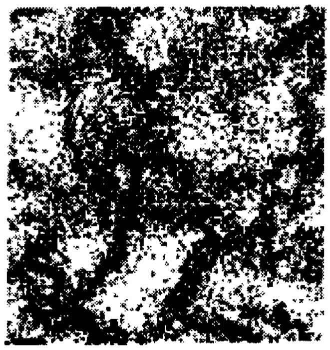


Fig. 6 Configuration of particle clusters in the space without gravity and fluid (Goldhirsch and Zanetti, 1993)

Yonemura et al. (1993) extended their work to the flow in a vertical channel. Fig. 7 shows the results.

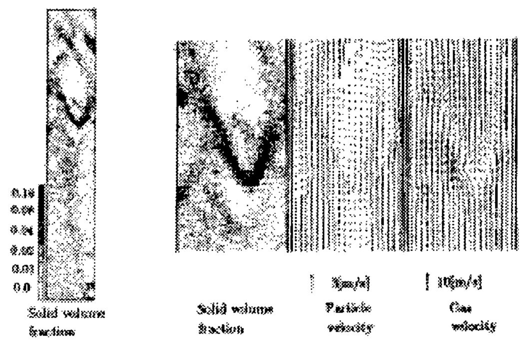


Fig. 7 Configuration of particle clusters in a vertical duct flow (Yonemura et al., 1993)

Corresponding to formation of clouds, strong turbulent field of fluid is produced. A recent work by Yamamoto et al. (2001) shows that the inter-particle collision does not always lead to particle clouds but in some cases it causes particle dispersion even if the collision is inelastic. Particle concentrations tend to be heterogeneous due to the interaction with vortices as in the first case. Such a particle heterogeneous concentration caused by vortices is destroyed near the wall by the inter-particle collision. In the core part of the duct, heterogeneous concentration caused by collision is dominant. However, it should be noted that the effects of vortices and collision on heterogeneity in particle concentration depend on the Stokes number, Reynolds number and nature of turbulence.

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