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A DISSIPATION-DISPERSION TURBULENCE THEORY AND ITS MODIFIED k-ε MODEL

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Abstract Based on the perturbation equation of the Navier-Stokes equation and the instability analysis of strongly nonlinear flow, a set of new control equations is presented featuring the interaction between dissipation and dispersion of turbulence. Three extra terms representing respectively the effects of extra strains, rotation and dispersion on the turbulent stresses introduced into the momentum equation. The defects of the original k-ε model are removed mainly by introducing new source terms. This modified k-ε model has advantages of simplicity, self-consistency and clarity of physics. It is able to handle complex flows and provides new perspectives for looking at a diversity of turbulence problems, such as intermittency, coherent structures, anisotropy, turbulent energy inversion and the cut-off of turbulence spectra.

Introduction

There are two basic directions for statistical turbulence modelling: first to average, then to analyze; or precisely the reverse. The first way is the well-known Reynolds average approach, which results in unclosed equations. Turbulence models for closing the Reynolds equation, so far, are not entirely satisfactory. As for the second direction, owing to the intractability of the non-linear hydrodynamic equations, hardly anyone has followed it.

Nowadays a new science is booming which has been called the third great scientific revolution of the 20th century along with relativity and quantum mechanics. Nonlinear science also sheds light on the analysis of the hydrodynamic equations. Based on the concept of fractal dynamics, a new method for analyzing strongly nonlinear equations is proposed. Fractal dynamics claims that random recurrent behaviour gives rise to a remarkable family of patterns, which appear on different scales at the same time with abrupt boundaries and sudden transitions. The quasi-self-similar patterns mean that the recurrent behaviour must be dominated by the same non-linear equation but with different scales at the same time. This idea suggests a general analytical method for non-linear equations as follows:

1) Multiply the original equation by dimensionless displacements of different scales.

2) Distinguish active and passive terms by stability or virtual-work analysis, the active terms being responsible for work production, the passive for work redistribution.

3) Add the active terms to the original equation to give a new equation which is able to describe the average behaviour with higher accuracy.

The general method has been used for analyzing both the instantaneous Navier-Stokes equation and the averaged Euler equation by Gao[1,2]. The analytical results provide important indicators for modelling Reynolds stress terms and for improving the production terms of the kinetic energy equation and the kinetic energy dissipation equation.

In order to obtain a better turbulence model, we must also pay attention to the following facts:

1) The discovery of coherent or organized structures in turbulent flow shows that turbulence is not absolutely a stochastic process, so it cannot be solved satisfactorily merely with the concept of dissipation.

2) Turbulent eddies simultaneously possess the properties of dissipation and dispersion. Miles showed that in a continuous stratified shear flow there exists an aggregation of innumerable discrete solitary wavelets[3]. C. C. Lin suggested that turbulence possesses the duality of wave and particle which is closely related to energy inversion[4]. G. Gao showed that there must exist some dispersion terms in the momentum equation of turbulent flow to capture the dispersive property of turbulence[1].

3) Turbulence energy inversion plays the role of another sink of turbulent energy besides dissipation. Since dissipation implies a generalized entropy rise, it excludes the possibility of energy inversion. However, possessing the duality of wave and particle, dispersion allows energy to be either positive or negative.

4) Intermittency offers another mysterious phenomenon of turbulence. In investigation of the canonical Burgers-K-dV equation, it has been shown that intermittency belongs to the results of the composite spatio-temporal instability. It is also one of the main properties of dissipation-dispersion interaction.

In the present development we attempt to take the above-mentioned phenomena into consideration.

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From the above, a set of new [illegible] equations for incompressible turbulent flow [illegible] momentum, turbulent kinetic energy [illegible] energy dissipation and energy equations [illegible]

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial}{\partial x_i} [illegible] \qquad (3)$$

$$\frac{\partial K}{\partial t} + u_j \frac{\partial K}{\partial x_j} = \frac{1}{\rho}\frac{\partial}{\partial x_j}\left(\frac{\mu_T}{\sigma_k}\frac{\partial K}{\partial x_j}\right) + \frac{G_k}{\rho} - [illegible] \qquad (4)$$

$$\frac{\partial \varepsilon}{\partial t} + u_j \frac{\partial \varepsilon}{\partial x_j} = [illegible] \qquad (5)$$

$$\frac{\partial t}{\partial t} + u_j \frac{\partial t}{\partial x_j} = [illegible] \frac{1}{\rho} \frac{\partial P}{\partial x_j} + \frac{1}{\rho}\frac{\partial}{\partial x_j}\left([illegible] \frac{\partial t}{\partial x_j}\right) [illegible] \qquad (6)$$

where [illegible] (I [illegible]) [illegible] 0).

[illegible]

[illegible]	C_1	[illegible]	C_3	[illegible]	[illegible]	[illegible]
$K \geq 0$, 0.2[illegible]; $K < 0$, [illegible]	1.44	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Discussion on Some Fundamental Problems of Turbulence

Based on the perturbation equation of Navier-Stokes equation including the [illegible] of the growth by destabilization, the new modified k-ε model provides us with new perspectives for looking at many of the perplexing problems of turbulence.

1. **Anisotropy** Anisotropy as a direct result of nonlinearity, mainly belongs to the characteristics of turbulent flow field rather than to the property of fluid medium. Based on a converting nonlinear analysis of Navier-Stokes equation, the modified model would arguably provide a clear explanation for anisotropy.

Adopting the Boussinesq eddy-viscosity concept, a traditional treatment for anisotropy is to look for an anisotropic viscosity coefficient. But from the viewpoint of random movement it is known that the local isotropy of turbulent eddies prevails. The movement of eddies has a strong tendency to isotropy except for those places where negative dispersion makes eddies move in a certain direction. Therefore, in a general sense, an isotropic turbulent viscosity coefficient μ_T is more convincing. Anisotropy should be expressed by extra terms in momentum equation. From equation (3) we get the corresponding Reynolds stress terms as

$$\tau_{ij} = \mu_t\left[\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{[illegible]}{2} - C_6 sign(u_i\Omega_{ij})\frac{K^{[illegible]}}{\varepsilon}\frac{\partial \Omega_{ij}}{\partial x_j}\right] + C_3\delta_{ij}u_i\sqrt{K}, \qquad (7)$$

It is obvious that by including the effects of strain, vorticity, dispersion and stretching processes, equation (7) can display non-isotropic features.

The effect of stretching on anisotropy gives an explanation for relaminarization. When turbulent flow accelerates violently, turbulence intensity may drop down and the flow finally returns to laminar. According to the production term **I** in G_k, stretching of streamlines always decreases the turbulent kinetic energy production, while compression of streamlines always increases the production. When stretching is strong enough, G_k becomes zero, but stretching does not influence G_t since there is no stretching term in G_t. A natural result is that the kinetic energy of turbulence rapidly decays leading to a laminar flow.

The effect of rotation on anisotropy provides a possibility of estimating turbulent intensity accurately in the places having strong vorticity. According to the production term I in G_k, rotation always reduces turbulent intensity, but it hardly ever leads to relaminarization. For example, owing to the effect of rotation on G_k, the turbulent intensity in the vortex region decreases and overcomes one of the defects of the original k-ε model, which usually considerably overpredicts turbulent intensity within a vortex. But rotation never makes a turbulent vortex laminar.

2. **Negative Dispersion and Energy Inversion** The action of positive dispersion has been explained in Ref. [1]. It plays a primitive role in forming turbulence by way of the interaction between dissipation and dispersion. But its effect on turbulence has been included in the experimental coefficient μ_T of

previous models before its real importance was recognized. Inheriting the conventional treatment, we will not introduce a new positive term in the present modified model, i.e. $C_0=0$, when $\mathrm{I}<0$.

Partial negative production is not a euphemism for dissipation. It thrusts turbulent energy back into mean flow and represents another sink of turbulent energy besides dissipation degrading turbulent energy to heat. The phenomenon is so odd that there has been immediate doubt as to whether it really exists, but the experimental evidence is quite unambiguous and there is really no conceptual difficulty. The substance of negative production is negative dispersion. The negative dispersion force has a special significance to determine energy inversion or feedback. The following is an example to illustrate its physical meaning.

Superimpose a field of fluctuating eddies on the background of a plane circular vortex field. This composite vortex field is made up of many concentric layers, each containing a population of arbitrary shaped micro-eddies (Fig. 1). Concentric circles b—b, a—a and c—c are streamlines of the background vortex. The tangential velocity distribution along the normal of streamline is shown in Fig. 1(b).

Observe two adjacent micro-eddies sandwiched between streamlines b—b, a—a and c—c. In the relative motion each eddy retains vorticity Ω due to the shear layers. Select O' on b—b and O'' on c—c respectively as the instantaneous centres of rotation for the inner and outer eddies. On a—a, the contracting pair of eddies impacts an upstream disturbing velocity and reduces the maximum tangential velocity to $u=\Omega l$. The velocity distribution along r across the vortex core boundary a—a is smoothed into the curve bHc instead of bac. This is the result of vorticity diffusion due to turbulent viscosity.

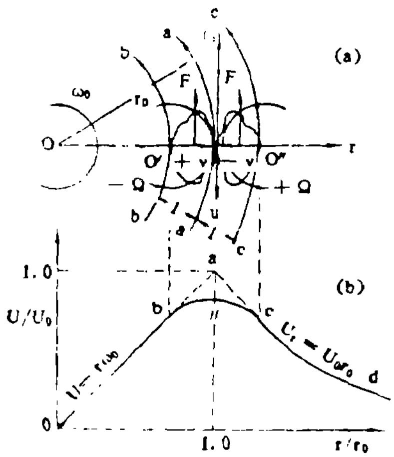

Fig. 1 Composite vortex field

Assume that the inner eddy is propagating radially outwards with disturbing velocity $+v$, and the outer eddy is propagating inwards with disturbing velocity $-v$. Each eddy with its angular velocity $\Omega/2$ about the intantaneous centre of rotation will generate the Coriolis force per unit mass $F=\Omega v$ acting in the same direction of U_0. The Coriolis forces in this way convert energy of the small scale fluctuating eddies into the directed collective flow. This is negative dispersion or energy inversion.

On streamline a—a, the second partial derivative of vorticity with respect to radius $\partial^2\Omega/\partial r^2$ reaches its maximum which produces strong negative dispersion in this region. The excited micro-eddies possess the duality of wave and particle. Their behaviors follow the Schrödinger equation. The field layer on both sides of a—a containing micro-eddies of scale l may be considered as a "wave guide belt". Only eddies with a certain scale or frequency can be rectified into directed collective flow. Since the eddies with longer wave length may penetrate the whole wave guide belt, while eddies with higher frequency within the wave guide belt may quickly oscillate in two-way, radially outwards and inwards, neither can be orientationally rectified to one direction. Corresponding to the limited rectifiable frequency scope, turbulent energy inversion causes a cut-off of the energy spectra of turbulence. J. Sommeria's experimental study of the two-dimensional inverse energy cascade in a square box provides strong evidence of the above principle[5].

When the strength of turbulence on opposite sides of the dividing streamline a—a is different, the amounts of rectified kinetic energy are different too. For example, in a Ranque-Hilsch vortex tube, the rectified eddies mainly come from the internal side causing a great drop of stagnation temperature inside the vortex after rectification.

In a near-wall boundary layer, the kinetic energy of disturbance comes only from the above layer where ejected and lifted fluid breaks down into smaller turbulent eddies and then sweeps down into the lower layer. Experiments show that a sharp peak in rate of production of turbulent energy occurs at the outer edge of the viscous sublayer at approximately 10—15 wall units from surface, a region of an inflection in the instantaneous longitudinal velocity profile. There are violent and frequent ejection and sweep motions that account for approximately 70% of the turbulent energy production in a boundary layer. The region between the linear sublayer and the logarithmic-law region, say $y^+=5-15$ wall units, has the biggest third-order derivative of velocity, so that strong negative dispersion occurs in the region. The fluctuating eddies transported from the above flow into the negative dispersion region are rectified to a unidirectional flow by the Coriolis force (Fig. 2), offering kinetic energy forming frequent ejections and maintaining the fullness of the turbulent boundary layer's profile. The stronger the intensity of turbulence of the above flow, the larger the amount of rectified turbulent energy. Therfore, when the turbulence intensity of the external layer increases with rise of disturbance or temperature, the drag of turbulent boundary surface drops.

3. **Intermittency** The mechanism of intermittency has been shown in Ref. [1] by the composite spatio-temporal instability of the 1-D canonical B-K-dV equation. Intermittency is a direct result of the interaction between dissipation and dispersion. There must be some intermittent phenomena in calculational results so long as the control equations contain some third-order terms. For example, the Large-Eddy Simulation model may have different third-order terms when its filtering function changes and thus produces different intermittent flow patterns. On a real 3-D turbulent flowfield the instability is more complicated than the 1-D canonical equation, but it still belongs to the realm of composite spatio temporal instability.

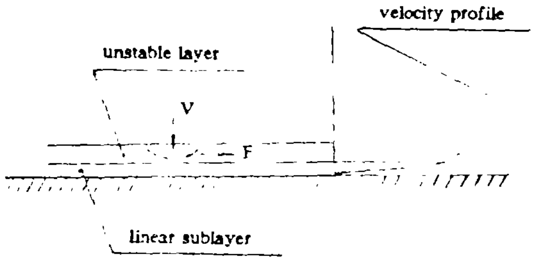

Fig. 2 Rectification of eddies in turbulent B. L.

There are two kinds of intermittent phenomena in turbulent flow. The first reflects the ubiquitous interaction between dissipation and positive dispersion. It is speculated on theoretical grounds that such a phenomenon of intermittency should be present at high wave number and with finer structures. Mathematically, the high-wave-number components are not very space-filling and their distributions in space should indeed be sparse. Intemittency appears to be present at all scales throughout turbulent flow, but after averaging the first kind of intermittency cannot be expressed in any statistical turbulence model since statistical methods require the ensemble of flows to be close to Guassian, i. e. the structures of the flow are space-filling.

The second kind of intermittency is related to the organized structures of turbulent flows, which arise from the interaction between dissipation and negative dispersion. Negative dispersion collects turbulent energy to produce orientated coherent flow, while disspation finally causes the coherent structure to break down. As an accompaniment to this breakdown, a new intermittent large-eddy structure will be formed consisting of a swarm of innumerable discretized smaller turbulent eddies. We may absorb the effects of this kind of intermittency into a calculation, so long as the negative dispersion terms appear in the turbulence model to create organized structures.

4. **Organized Structure** One of the major unresolved physical features of turbulent flow is that turbulence is characterized by a remarkable degree of order. The study of turbulence structures, while clearly revealing their presence and importance, has so far not resulted in any new theoretical idea that directly assists modelling. At present it seems that in place of "theory without structure" we have "structure without theory". In fact, the organized structure is another direct result of the interaction between dissipation and dispersion. A full appreciation of a deterministic and comprehensible chaotic flow behaviour should be possible within the framework of the dissipation and dispersion cooperative theory of turbulence.

There are two questions pertinent to understanding the mechanism of organized structures. Firstly, what kind of force controls the generation, development and final breakdown of the organized structures? Secondly, what is the key to maintaining repeatedly periodic structures and retaining a permanent imprint of their initial state? The answer to both questions is that the primary cause is negative dispersion. To illustrate this assertion, let us look at the formation and evolution of the entrainment structures in turbulent free shear layers.

There are plenty of homogeneous turbulent eddies produced by the shear stress in a free shear layer. By a random chance in time and space, due to the negative dispersion and energy inversion, some individual eddies start to absorb the energy of other smaller eddies and gradually become stronger and larger. This is a typical formation process of the dissipation structure proposed by Prigogine. The extra rotation term in the momentum equation has the power to adjust the interval between two large eddies. For example, if twolarge eddies are located too closely, the turbulent viscosity and its gradient in the middle area increase and this makes the rotation term larger and causes the two large eddies to separate from one another. The final result is that several dominant vortices align in a mobile axis system with adjustable intervals (Fig. 3).

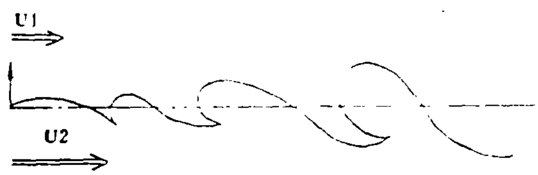

Fig. 3 The entrainment structure in the interval area of the aligned vortices

A natural result is that some spanwise entrained structures appear in the **interval** area of vortices.

From the above instance it is seen that if certain velocity, turbulent viscosity and kinetic energy profiles are given, the extra terms in the momentum equation simultaneously give a combined orientation force which determines the curling direction of an organized structure.

One of the most complex structures of turbulence is in the wall turbulent flow. The wall streak structures and intermittent turbulent production events(bursts) in the near-wall region are generally referred to as the coherent structures in the wall boundary layer. Negative dispersion also plays a dominant role for the wall coherent structures. A brief explanation of their is as follows.

1) **The Wall Streaks** Due to the continuity of flowing fluids, many random disturbances may cause corresponding solenoidal motions, including isolated vortices and pairs, towards many directions, but only those vortex filaments which have the same direction as the streamlines may keep long-duration stability[1]. Absorbing the turbulent energy of the surrounding smaller eddies through negative dispersion, the randomly produced streamwise vertical motions gradually become stronger until their diameters reach the order of 30 to 40 wall units. Further growth of their diameters is limited by the fact that turbulent intensity beyond 40 wall units decreases a lot and cannot provide enough turbulent energy to be rectified to overcome dissipation. The final result is that many individual streamwise vortices with a dimension of the order of 30 to 40 wall units stand side by side as streaks with an average transverse spacing of approximately 80 to 100 wall units. The appearance of the wall streaks is random both in time and in space, but their direction, structure and scales are deterministic.

2) **The Burst Circle** As mentioned in section 2, there is a strong negative dispersion region in the layer of $y^+=5-15$ wall units which absorbs and stores the turbulent energy sweeping down to the near-wall region and induces ejection. The bursting turbulence production is preceded by the somewhat more gradual formation in the region $y^+=20-30$ wall units, where positive dispersion, acting in conjunction with shearing, becomes the main source of turbulence.

An ejection is always accompanied by a lifting in a peak stage, while a sweep is always accompanied by a falling in a valley stage. The lifting and falling forces are produced by the extra rotation and stretching terms in the momentum equation. For instance, when the ejected fluid is accelerating along the longitudinal direction, due to stretching the turbulent intensity and viscosity are decreasing along the same direction. The component of the rotation term in $y$direction $(\Omega_{ty}/2)\partial v_T/\partial x$ is positive and provides a strong lifting force. The sweep process is exactly the reverse. A burst cycle consists of an ejection and a sweep. Therefore ejection and sweep events are about equally numerous. Turbulence burst after an ejection can be mainly attributed to the sudden retardation of the ejected fluid in the final stage.

3) **The Turbulent Spot** A turbulent boundary layer consists of many amalgamated individual turbulent spots. A turbulent spot again consists of many wall streaks and ejection-sweep cycles. The form and growth of a turbulent spot are controlled by a destabilization process. therefore, the ensemble diamond form of a turbulent spot must be covered by a stable film of fluid under which there is a variety of coherent structures. The turbulent energy production is zero on and beyond the hood. Letting $G_k=0$ be an equation and neglecting small terms in it, we may directly get a solution to express the irrotational motion around a spot. A surprising result is that the irrotational motion is composed of a diamond curved surface which is just like an intact turbulent spot.

So far, it seems that the dissipation-dispersion cooperative theory of turbulence contains the power to handle both random and deterministic elements of turbulence. In this sense, it belongs to a new generation of turbulence theory connecting the statistical movement and the structural movement of the scientific study of turbulence.

Brief Discussion of Computed Results

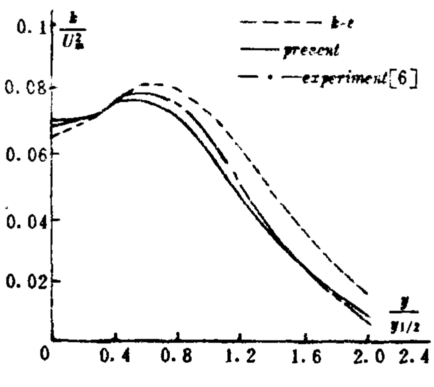

Fig. 4 Turbulence energy profiles in plane jets in stagnant surrounding

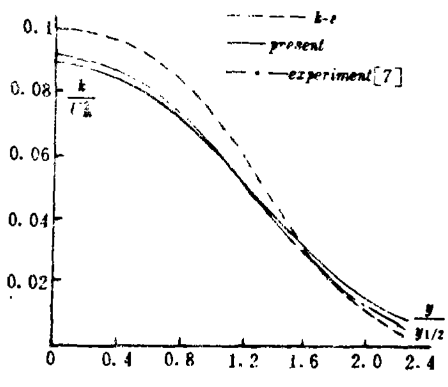

Fig. 5 Turbulence Energy Profiles in round jets in stagnant surrounding

The computed and measured behaviours for the plane and round jets are compared in Figs. 4-6 and in table 3. The corresponding kinetic energy profiles shown in Figs. 4 and 5 are in satisfactory accord. The difference in the shape of turbulence kinetic energy profiles between the round and plane jets is correctly reproduced by numerical computations. The improvement of the k profile of the round jets, especially in the near-axis region, is mainly attributable to the extra stretching term in the momentum equation. In the case of round jets, the strength of the velocity decay in the near-axis region is far greater than for the plane jets. Since the velocity decay effectively increases the kinetic energy production, the k profile of the round jets exhibits a monotonic decrease from the axis while the k profile of the plane jets is like a hump with its maximum at $y/y_{1/2}=0.65$. The most interesting results appear in Table 3. The present computations show a great improvement over the original k-ε model and, in fact, the anomaly of the round jet/plane jet has been solved.

Table 3 Rates of spread of plane jets

Flow	Experiment	Original k-ε model	Present model
Plane jet	0.110	0.109	0.111
Round jet	0.086—0.093	0.114	0.092

The reason for the improvement of the spread rate prediction is also due to the extra stretching term in the momentum equation. The component of the stretching term in y directions $(C_3V/\rho)\partial\sqrt{K}/\partial y$. From Figs. 4—5 it is shown that this term is always negative and suppresses the rate of spread for the round jet, but it is positive and helps to increase the rate of spread within the region from the axis to $y=0.65y_{1/2}$ for plane jet. Figure 6 shows the measured and predicted dissipation profiles of the round jets. Since there is no extra stretching term in the dissipation production G_ε of the present model, a hump-like profile of dissipation has been obtained. Otherwise, if one puts the extra stretching term into G_ε the level of ε decreases monotonically from the axis, similar to the k profile in the round jets. This gives an important support for the view that G_K and G_ε should not be equal and that G_ε should not contain the extra stretching term in G_K.

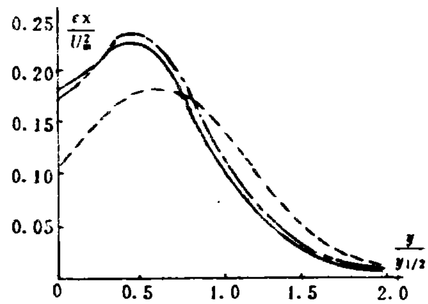

Fig. 6 The measured and predicted ε profiles of the round jets (——Predicted by present model —·—Exp. LDA data, energy balance ————Exp. HW data, energy balance[8])

Because the modelled differential equation for free turbulence yields demonstrably incorrect results near a wall, various ad hoc functions (at least up to 5 in number for k-ε methods) are conventionally added in an effort to eliminate this shortcoming. Since our present modified k-ε method is based on a thorough consideration of the nonlinearity of turbulent flow, the appearance of the proposed k-ε method undergoes a substantial change. Group I of G_K always subtracts $\mu_T\Omega_{ij}^2/4$, which makes a great contribution to removing the shortcoming that the original k-ε model considerably overpredicts the turbulent intensity and turbulent viscosity in the near-wall region ($y^+<40$). The cut-off state of G_K and G_ε in the region of about $y^+=10$ also offers an important contribution to the correct prediction in the near-wall region. An exciting discovery arising from this improvement is that the same modified k-ε method is effective for both free flow and near-wall flow!

Figure 7 shows excellent agreement of the friction factor C_f and the pressure gradienparameter $\beta = (\delta^*/\tau_w)\partial P/\partial x$ with the experimental measurements for unseparated diffuser flows (case No. 0141 of 1981 Stanford Conference on Turbulent Flows). This case is a severe test of prediction methods for turbulent boundary layer subjected to a strong adverse pressure gradient. Since the onset of flow detachment in the separation process is related to skin-friction coefficient C_f as it approaches zero, it is very important that C_f be well predicted. Various former k-ε methods usually overestimate C_f by 100% or more near the detachment region. Using the present model to calculate this case, excellent accord of the skin-friction, the velocity profiles and the Reynolds-stress distribution with experimental data is obtained. None of these three parameters differed by more than 10% from the experimental data. A more interesting result is associated with the predicted β curve. This pressure-gradient parameter exhibits a sharp change in slope at $x=2.50$ then, after a region where it increases steeply, a marked reduction in slope occurs at $x=2.70$. It has been found through numerical tests that the

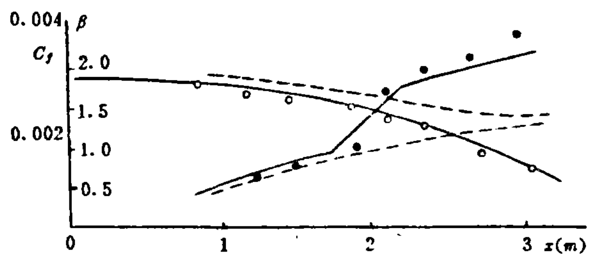

Fig. 7 The measured and predicted C_f and β distribution of an unseparated diffuser flow (• & • measurements, ————k-ε model, ——present model, C_f: skin-friction, β: pressure gradient parameter)

first turning point exactly corresponds to the location where the kinetic energy production G_K departs from its cut-off state, while the second point corresponds to the location where the dissipation production G_ε likewise departs from its cut-off state. The reason that G_ε departs from the cut-off state later than G_K is the lack of extra stretching term in G_ε.

The modified k-ε model has been found able to handle complex turbulent recirculating flows. Figure 8 shows substantial improvement in the calculation of a vortex field behind a triangular bluff-body: 1) The prediction of the vortex length increases by 22% compared with the original model, which brings agreement with the actual length within 2%. This improvement may be mainly attributed to the negative dispersion term in the momentum equation, which causes partial turbulent energy inversion within the vortex edge region. 2) The turbulent intensity distribution is greatly improved both within the vortex region by the extra rotation term and in the vortex tail region by the extra stretching term. 3) The position and scale of the voscous vortex core achieves good accord with Fujii's experimental measurement using LDA[9]. The original k-ε model usually gives too large viscosities and this moves the eye of the vortex too close to the body. These shortcomings have been removed in the present model due to the combined action of all the extra anisotropic terms.

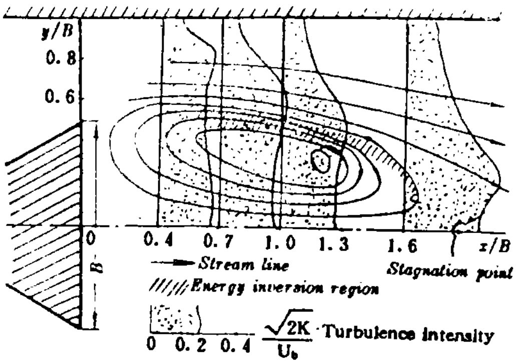

Fig. 8 Computational result of wake vortex field behind a bluff-body

Some intermittent coherent structures of free shear flow and wall flow appear in the above calculational results. If a finer calculational grid size were adopted, more details of the structures would be available.

Though the modified k-ε model based on the dissipation-dispersion cooperative turbulence theory is still need more testing and further adjustment, it has been shown capable of handling both complx free flows and near-wall flows using the same equation and coefficients.

Conclusion

Based on the disspation-dispersion cooperative concept, the k-ε model has undergone a thorough reexamination. New extra terms representing respectively rotation, stretching and dispersion are introduced not only into the turbulent kinetic energy production G_K and dissipation production G_ε but also into the momentum equation. A series of complex problems of turbulence, such as anisotropy, extra effects of rotation and stretching, coherent structures and turbulent energy inversion, are taken into consideration both in physics and in modelling and tested by calculations.

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