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Progress in Smart Control of Turbulence

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Abstract

During the last five years, we have made an extensive research and development study on smart control of turbulence within the framework of the Project for Organized Research Combination System by the Ministry of Education, Culture, Sports and Technology of Japan (MEXT). The present report summarizes the major scientific and engineering accomplishments made by the participating two working groups, *i.e.*, WGs for active control of turbulent flow and for turbulent combustion control, with the former being composed of MEMS and fluid properties working subgroups. Remaining issues for the future investigations are also described.

1. Introduction

The modern turbulence research has a history of more than hundred years since the Osborne Reynolds' pioneering work in the late 19th century. Its three major aims have been to understand highly nonlinear turbulence mechanics, develop predictive methods for turbulent flow phenomena and devise schemes of controlling them. It was this third target that we focused upon, and our efforts have been directed toward innovating highly advanced control methodologies. It is well known that control of turbulent flows and associated transport phenomena should be a key in many engineering practices such as energy saving, efficient production process, securing high quality products, and resolving global environmental problems. Its impacts on future technology and human life would be enormous through manipulation and modification of turbulent drag, noise, heat transfer, mixing as well as chemical reaction.

A collaborative research project on "Smart Control of Turbulence: A Millennium Challenge for Innovative Thermal and Fluids Systems" was started in the fiscal year of 2000, being supported through the Organized Research Combination System by the Ministry of Education, Culture, Sports, Science and Technology. Three national laboratories and several universities participated. In the project, two major control areas were identified and their working groups on turbulent wall shear flow and combustion were formed. The wall turbulence control included development and application of microelectromechanical systems (MEMS) sensor/actuator devices, and introduction of additives such as micro bubbles and surfactants. The turbulent combustion control aimed at reducing toxic emissions and stabilizing premixed lean combustion flames. Advancing powerful research tools such as large-scale numerical simulation methods and advanced Laser diagnostics techniques were also an important target. The specific project targets and their backgrounds are summarized in this paper.

1.1 Active feedback turbulence control with distributed sensors and actuators

Active feedback control of wall-turbulence has been investigated extensively since the beginning of 1990's. With the recent development of MEMS technology, it is now possible to fabricate micro-scale arrayed sensors/actuators and integrated control systems, which are ideally designed and optimized in the theoretical and numerical studies. The effort of this working group has been devoted to develop an active feedback control system for reduction of skin friction drag in turbulent wall-shear flows. In order to achieve this goal, extensive R&D studies were made on hardware and software components. These components were integrated into a control system. Wind tunnel experiment was then repeated in order to assess the effectiveness of active feedback control systems developed.

Another research target was to control and mitigate flow separation, which causes energy loss and also leads to malfunction and deterioration of fluid machinery. Through separation control, the flow pattern can be kept close to that given by inviscid flow theory, resulting in large lift and small drag. Although numerous studies were made over the last several decades, the application of feedback system to separation control has scarcely been investigated together with possible employment of MEMS devices. In this project, we aimed at establishing a sophisticated control system for separation on an airfoil. For this purpose, a closed loop control system was constructed with actuators and sensors newly developed.

1.2 Turbulence control by manipulation of fluid properties

A small amount of additives to liquid flow causes distinct turbulence modification. This is a promising scheme for real applications, because the degree of drag reduction by additives, for example, can easily reach several tens of percent, while the cost for control remains relatively small. For drag reduction in external flows, *e.g.*, a sea water boundary layer around the ship, addition of micro bubbles is one of the most hopeful methods because of their small environmental impact. In internal flows such as those observed in district heating/cooling systems, surfactant is most suitable because of its long life.

This working subgroup was organized to study the turbulence control through functionalization of a fluid by introducing bubbles or surfactant. In both approaches, a variety of application has been so far tested, but the drag reduction mechanism is still unclear because of the lack of the detailed knowledge on the phenomena of two-phase and non-Newtonian fluid flows near a solid wall, particularly at high Reynolds numbers. Therefore, the primary target was set to elucidate the dynamical mechanism of turbulent drag reduction. Full scale ship test for bubble injection and heat transfer management study for surfactant solution were also carried out.

1.3 Active control of turbulent combustion

Lean premixed combustion is a promising way to reduce toxic emissions such as NOx. However, this combustion mode often becomes unstable, so that effective control methods are needed to achieve stable combustion over a wide range of operation conditions. This WG focused upon active control technique, which has a potential to achieve wide-range stability in lean premixed combustion. An integrated control system composed of sensors, actuators and regulating systems is designed and installed in a methane lean premixed swirl-stabilized combustor. In a final assessment experiment, instabilities such as combustion oscillation are successfully suppressed. The combustion control system with secondary fuel jet and a mixed H_2/H_∞ control algorithm succeeds in decreasing the sound pressure level by 28dB. A considerable degree of knowledge on turbulent combustion control has also been accumulated during the course of this project.

2. Active feedback turbulence control with MEMS devices

2.1 Wall turbulence control

2.1.1 Skin friction modification through manipulation of turbulence

In order to clarify the ultimate limit of skin friction reduction control, a general expression is derived of the componential contributions that different dynamical effects make to the frictional drag in turbulent channel, pipe and plane boundary layer flows (FIK identity, see, Fukagata *et al.*, 2002). It is shown that the local skin friction can be decomposed into four parts, *i.e.*, laminar, turbulent, inhomogeneous and transient components, the second of which is a weighted integral of the Reynolds stress distribution. The FIK identity provides a basis that the manipulation of near-wall Reynolds stress is primarily important for drag reduction control in wall turbulence, and also a general guideline for developing various control schemes and analyzing their dynamical effects.

2.1.2 Sensors and actuators

Arrayed micro hot-film wall-shear stress sensors were designed and fabricated through MEMS processes. The geometry of sensor unit was optimized with the aid of numerical simulation of unsteady conjugate heat transfer and heat conduction around a sensor with an air cavity beneath the viscous sublayer flow. The sensor developed, which is shown in Fig. 1, has a frequency response (about 500 Hz) high enough to capture the characteristic turbulence structures in a wind tunnel test. The backside contact technology was adopted for wiring, and this resulted in an extremely flat surface

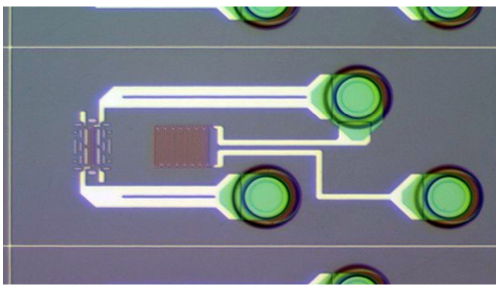

Fig. 1 Micro hot-film wall shear stress sensor with electrical through-wafer interconnects.

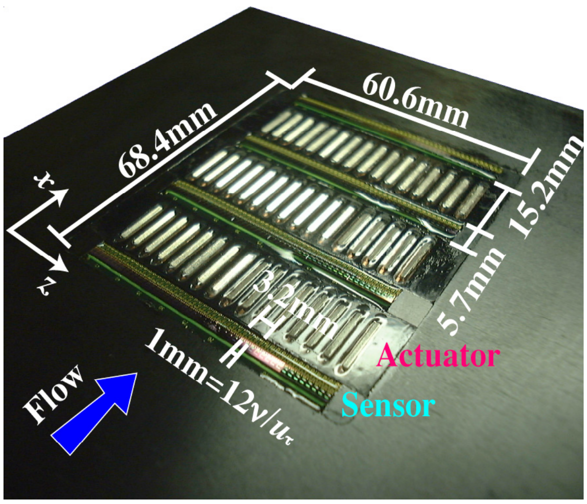

Fig. 2 Active feedback control system for wind tunnel experiment.

of the sensor, so that it did not disturb the flow field (see, Suzuki *et al.*, 2005; Yamagami *et al.*, 2005).

Miniature magnetic actuators have been developed and assembled into an array unit (Suzuki *et al.*, 2005). An actuator has a deformable silicone membrane of 14 mm in length and 2.4 mm in width with a small piece of permanent magnet. The maximum deformation height is about 200 μm and the resonant frequency is about 600 Hz. The design of actuator has been repeatedly improved through a finite element analysis of magnetic field (Yamagami *et al.*, 2005).

Different types of actuators were also developed for future possible applications, *i.e.*, electrostrictive actuators (Pimpin *et al.*, 2004) and see-saw type electromagnetic actuators (Yamagami *et al.*, 2005). The fabrication of both actuators is completely compatible with MEMS process.

2.1.3 Control algorithm

In order to facilitate the introduction of devised control schemes to a real control system, adaptive schemes based on the genetic algorithm (GA) have been mainly studied with supplementary control strategies gained from optimal (or suboptimal) control theory and physical arguments. The control scheme thus developed was first verified by direct numerical simulation (Morimoto *et al.*, 2002), and then used in the experiment (Suzuki *et al.*, 2005). Several new theoretical findings were obtained regarding the active feedback control of wall-turbulence (see, *e.g.*, Fukagata *et al.*, 2005).

2.1.4 Integrated system

An active feedback control system was developed by integrating 192 micro hot-film shear stress sensors, 48 miniature magnetic actuators, and digital signal processors, as shown in Fig. 2. The system was installed in a wind tunnel, where a 2-D turbulent channel was fully developed. By using the GA-based adaptive control, the friction drag measured by the downstream sensor was reduced by 7−10% (Suzuki *et al.*, 2005). Modification of turbulence structure was studied by using the laser Doppler velocimetry.

A prototype of MEMS-based integrated control system was also developed (Yamagami *et al.*, 2005). It consists of micro hot-film shear stress sensors, MEMS-fabricated see-saw type magnetic actuators, and custom-made analog VLSI. The assessment of this system remains to be a future study.

2.2 Separation control

2.2.1 Sensors and actuators

Two kinds of new micro sensors have been developed. In order to sense an instantaneous flow direction near the wall, namely, to detect local flow separation, a double cantilever flow sensor (DCFS) was fabricated. It was demonstrated that DCFS can detect not only flow direction, but also local flow velocity as well as skin friction with high temporal resolution (Pang *et al.*, 2004).

A fiber Bragg grating sensor (FBGS) was another outcome. Optical fibers with Bragg gratings were originally used in monitoring integrity of structures, and it is the first attempt to apply this sensing technique to fluid measurements (Segawa *et al.*, 2003). As shown in Fig. 3, the turbulent wall skin friction was successfully measured by using FBGS.

Solid fin-ype vortex generators have been known as a flow control device. A micro jet vortex generator (MJVG) was developed to enhance advantages and minimize disadvantages of the conventional vortex generators. It is a continuous jet and can generate a single, longitudinal vortex with an arbitrary strength and extent (Abe *et al.*, 2005). An example of co-rotational vortices generated

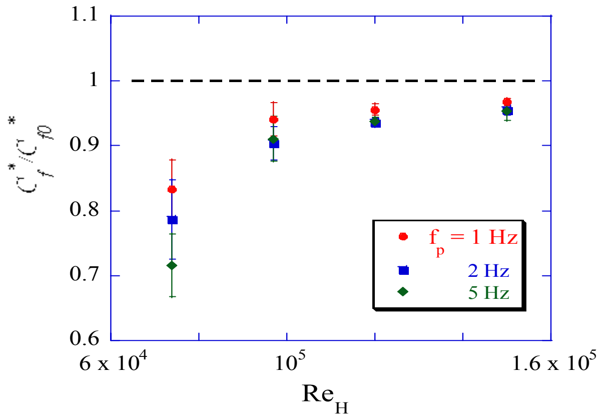

Fig. 3 Drag reduction measured by FBGS.

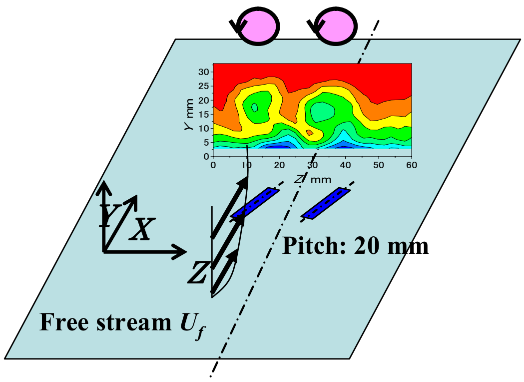

Fig. 4 Co-rotational vortices generated by MJVG.

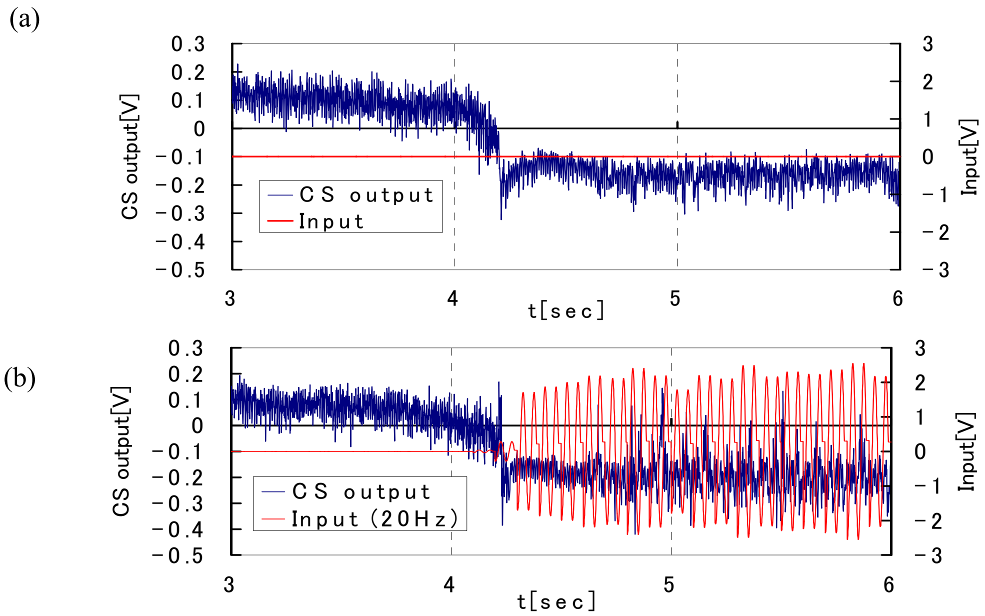

Fig. 5 Closed loop control of separation on a pitching airfoil: (a) CFS output under no control; (b) CFS output under control.

by MJVG is shown in Fig. 4. An array of MJVG was actually installed on the MEL001 airfoil to examine its performance. For flows at a Reynolds number range of O(10^4) to O(10^5), an appreciable increase in the lift coefficient is confirmed (Abe, *et al.*, 2005). Moreover, it is found that the continuous use of MJVG suppresses the time variation of lift unlike the synthetic type jet.

Spanwise wall oscillation has been known to bring remarkable turbulent drag reduction, although it is difficult to design and install such mechanism in a real system. Therefore, an effort was made to seek for a device, which offers similar wall-oscillation-like effects. As a result, an alternative suction/blowing jet (ASBJ) was developed and, in a preliminary experiment, its drag reduction effect was observed (Segawa *et al.*, 2003).

2.2.2 Control system

By using the devices above mentioned, a closed loop control system for airfoil flow separation was constructed for the first time as shown in Fig. 5 (Nishizawa *et al.*, 2005). The control system was found to work properly as designed. Further improvement of the control system can be expected when we optimize each component of the system, especially actuator.

3. Turbulence control with additives

3.1 Establishment of standard database on drag reduction by microbubbles

Almost all of existing experimental data of microbubbles were taken in laboratory at scales of 1 or 2 m. However, in order to assess the practical use of microbubbles, it is necessary to know how far downstream after injection of bubbles the skin friction reduction persists. Therefore, basic experimental data over a length of at least a few tens of meters are needed. We obtained the data of up to 2 m using a small high-speed water tunnel, and those of up to more than 40 m by towing a 50 m-long flat plate in a 400 m-long towing tank as shown in Fig. 6. In those experiments, a slot injection method, which had been recognized as the best bubble injection scheme, was consistently used. Also, local void ratio distributions across the boundary layer, which were known to have strong correlation with the skin friction reduction, were measured. Thus, comprehensive and consistent experimental database covering both small and large scales have been obtained (Kodama *et al.*, 2004). They will be published in periodical journals and utilized as standard experimental data of turbulent flows with microbubbles.

A real ship test for microbubble effect will soon be carried out. In February 2005, microbubble injection devices tuned for a fully loaded condition will be installed into a 120 m-long cement carrier (Pacific Seagull owned by Azuma Shipping Co., Ltd., Fig. 7). In this full-scale experiment, 4.3 to 8.5% net fuel cost saving is expected for 30 months. Another full-scale installation tuned for a ballast condition is expected in October 2005 (Kodama *et al.*, 2004).

Fig. 6 A 50 m-long flat plate towed in a 400 m-long towing tank for microbubble experiment.

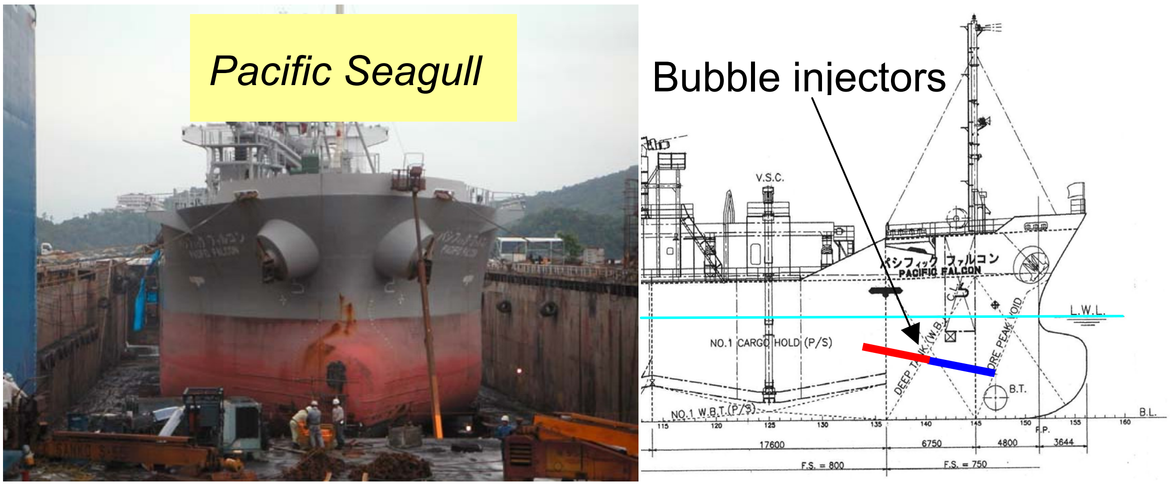

Fig. 7 Full-scale experiment using a 120 m-long cement carrier.

During the course of work, the following techniques for controlling the bubble size have been developed (Moriguchi and Kato, 2002; Kawamura *et al.*, 2004):

(1) Shear stress manipulation at the air injector (water-jet method, contraction method),
(2) Different air injection modes (porous plate, array-of-hole plate, slot plate),
(3) Use of cavitation in a Venturi tube,
(4) Separation of dissolved air by decompression,
(5) Use of additives such as 3-pentanol.

As shown in Fig. 8, it was found, however, that the merit of making bubbles smaller than that naturally decided by the local turbulent shear flow is small. This is a new finding which denies the previously dominated idea that smaller bubbles are always preferred. Thus, it was concluded that the use of slot plate is desirable for practical applications for its small pressure loss and larger bubble size.

Moreover, the above experimental evidence that the drag reduction is independent of the bubble size when the void fraction distribution is constant has given a great insight into the drag reduction mechanism. This has then led to the experimental and numerical efforts in the project concentrated towards the drag reduction mechanism.

3.2 Validation and exploitation of experimental measurement and numerical simulation

3.2.1 Measurement system with PIV/SIT

For the present experimental investigations of complex turbulent two-phase flows, a particular care has naturally been paid to measurement techniques. An optical measurement system with PTV/SIT for microbubble flow was extensively assessed (Kitagawa *et al.*, to appear; Fujiwara *et al.*, 2004). The resultant remarks derived from the optical measurement are as follows:

(1) Measurement system developed can acquire both images of liquid and bubble at the same time (Fig. 9),
(2) Reynolds stress in a liquid, $u'_L v'_L$, decrease in a microbubble flow,
(3) Bubble deformation causes the decrease of Reynolds stress in liquid around a bubble (Fig. 10).

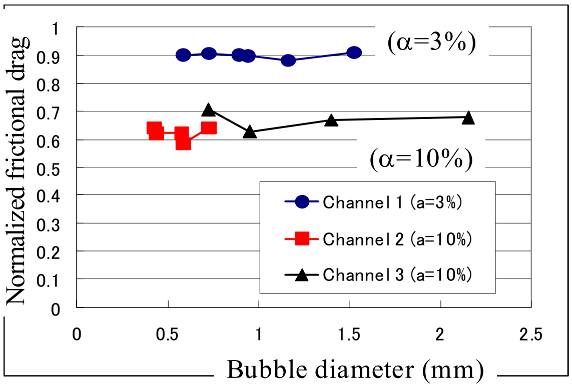

Fig. 8 Effect of bubble diameter on frictional drag.

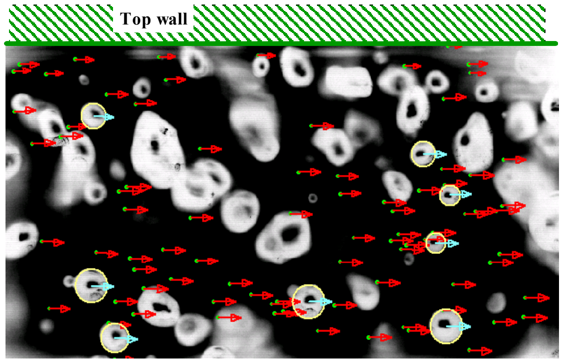

Fig. 9 Image analysis result of measurement system with PTV/LIF/SIT.

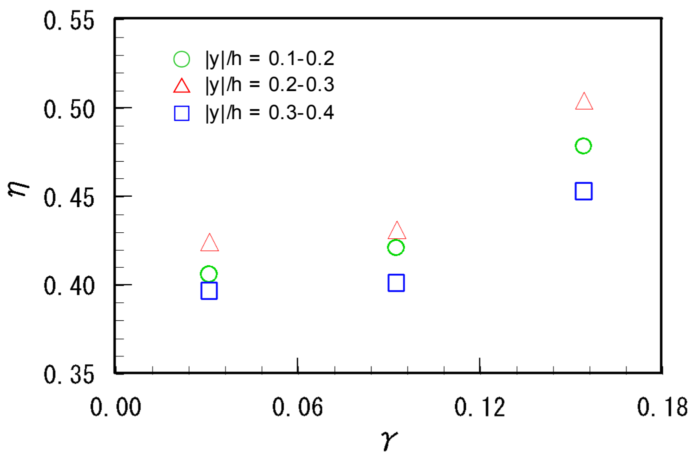

Fig. 10 Bubble deformation ratio($\gamma = \frac{L-D}{D}$) vs. frequency of occurrence of negative Reynolds stress ($\eta = \frac{N(u'v' < 0)}{N(total)}$) (Experiment by PTV/LIF/SIT).

3.2.2 Numerical simulation of turbulent bubbly flow by DNS/LES

Following numerical methods have been developed in order to simulate bubbly flows, in which different flow scales are to be considered (Nakatani and Kawamura, 2005; Sugiyama *et al.*, 2004):

(1) Highly accurate simulation for flows around a single bubble,

(2) Direct numerical simulation (DNS) for flows with spherical bubbles,

(3) DNS based on a front-tracking method for flows with deformable bubbles,

(4) Large eddy simulation (LES) based on the front-tracking method for flows with bubbles (Fig. 11),

(5) Force coupling (FC) simulation with force monopole as well as dipole considered,

(6) Eulerian-Lagrangian simulation for turbulent bubbly flows in a two-way coupling method.

The most significant conclusion was obtained by numerical analysis based on the method of (4) above; at the friction Reynolds number larger than about 1000, the turbulence structure is modulated

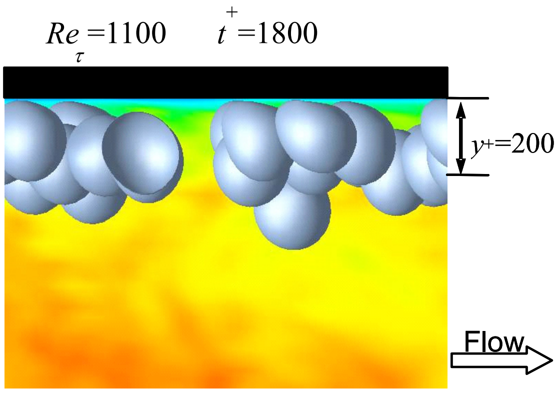

Fig. 11 Distribution of bubbles near the wall (LES of the bubbly turbulent flows).

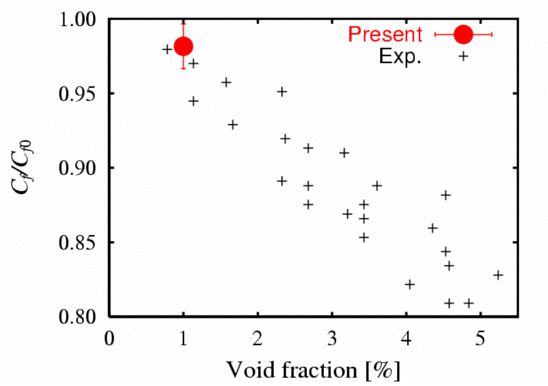

Fig. 12 Comparison of LES result and experiment - effect of void fraction on frictional drag coefficient.

so as to reduce the skin friction by the bubble motion. In the LES at the friction Reynolds number of Re_τ = 1100 and the void fraction of 1%, the drag reduction is reduced by about 2%, as shown in Fig. 12, in good agreement with the experiment performed by Moriguchi and Kato (2002). The uv-correlation in bubbles becomes lower than that in the liquid, and such a result compares quantitatively well with the PTV measurement obtained by Kitagawa *et al.* (2004). This result is consistent with those obtained by the experimental group and the turbulence suppression by larger bubbles than eddies.

3.3 Drag reduction with surfactant

The following pieces of work have been carried out for the fundamental study on the mechanism of drag reduction by surfactant additives:

(1) Detailed measurement of drag reducing flow in 2D channel with LDV and PIV,
(2) Simultaneous measurements of temperature and velocity fluctuations in thermal boundary layer in a channel by fine-wire thermocouple and LDV (Li *et al.*, 2004),
(3) DNS with non-Newtonian constitutive equation,
(4) Numerical and experimental investigation of heterogeneous injection of additives,
(5) Basic study and application test for micellar network destruction device.

As a result, it is found that the surfactant drag reduction is caused by suppression of turbulent diffusivity. This skin friction modulation can be formulated through a simple relationship with the frequency and strength of turbulent bursting in both normal and drag reducing flows. The numerical simulation reveals that a sophisticated upwind scheme makes flow simulation stable even at high Weissenberg numbers (Yu and Kawaguchi, 2004). Thus, the detailed process of loss of drag reduction at high Reynolds numbers was clarified (Yu *et al.*, 2004). In simple flow geometry, heat transfer suppression is found to take place in similar magnitude of drag reduction, and it is possible to increase heat transfer coefficient by “extension conscious” micellar network destruction device.

4. Turbulent combustion control

4.1 Basic study on combustion control

4.1.1 Sound generation mechanism

Sound generation mechanism has been investigated by direct numerical simulation (DNS) of compressible, chemically reacting flows (Miyauchi *et al.*, 2001). The effects of heat release on the sound generation mechanism are investigated in fully developed turbulent state, and it is found that the key to develop an effective control scheme for combustion noise mitigation is how to suppress the fluctuations of heat release rate and how to control the fine scale eddies, which are related to turbulent energy dissipation rate and Reynolds stresses.

4.1.2 Development of measurement method

Advanced measurement methods such as simultaneous CH-OH PLIF/PIV and a time-resolved PIV have been developed to investigate local flame structures (Tanahashi *et al.*, 2003). This system is potentially applicable in a frequency range from several hundreds Hz to several tens kHz, and the mechanism of the noise reduction by secondary fuel injection are also clarified. Clarifying a detailed structure of the flame in the combustion control has become possible by using this measurement method.

4.1.3 Numerical simulation

Detailed information about local structure of turbulent flames brings us a broader view, for example, on the relationship between heat release rate and pressure fluctuations, and this is therefore quite important for development of active control scheme. To investigate local flame structure of turbulent flames, DNS computations have been conducted for various combustion regimes with detailed and reduced kinetic mechanisms (Mizobuchi, 2003; Tanahashi *et al.*, 2004), and it has been shown that fine scale eddies in the unburned turbulence have an important role to determine the local flame structure. Effects of equivalence ratio on the local flame structure and local extinction mechanism of turbulent flames are also investigated.

The LES computations are also performed to investigate the mechanism of unstable combustion and to examine the effect of secondary fuel injection on combustion dynamics. It has been shown that combustion dynamics in a lean premixed combustor is successfully simulated by LES, and unstable oscillations are well simulated (Shinjo *et al.*, 2004).

4.1.4 Sensors and actuators

A chemiluminescence emission sensor has been developed to investigate the dynamics of the flame and its instabilities within the combustion chamber. It has been used to build active control schemes by providing detailed information on the temporal behavior of the secondary fuel injected. In parallel, Laser Induced Plasma Spectroscopy (LIPS) has been developed to provide information for understanding the actual chemiluminescence signal measured and its relation with stoichiometry (Zimmer *et al.*, 2004). Finally, to achieve the active combustion control, diode-laser absorption sensor (DLAS) has also been developed. It has been shown that DLAS can measure high frequency fluctuations of temperature and mole fraction. These results suggest that DLAS is a good candidate for active combustion control.

Various actuating modes have been studied and assessed, *i.e.*, speakers (Hayashi *et al.*, 2002) and secondary injection and piezo valves (Ikame *et al.*, 2002), for the adjustment of combustion control. By applying the speaker and the piezo valve to a small combustor, excellent performance is obtained. Finally, we evaluate the performance of the secondary injection valve for a real combustor and adjust the demonstration experiment from a practicality viewpoint.

4.1.5 Control algorithm

We studied the control method, which was based on a closed-loop control system with a sensor and an actuator, and finally integrated a mixed H_2/H_∞ controller for combustion control designed by using the system identification method. The controller has successfully suppressed the combustion oscillation. Consequently, it is possible to improve a variety of combustors by using the same method, since this control algorithm has robustness and offers high control performance (Harumi *et al.*, 2003; Sato *et al.*, 2004).

4.2 Experimental combustion control

Combustion oscillations are a result of strong coupling between the oscillations of pressure and heat-release rate, so the key in active combustion control is to break this in-phase coupling. There exist several methods of actuation to achieve this, for instance, loudspeakers, adjustment of main fuel/air flow rates and secondary fuel/air injection. Among these, secondary fuel injection was considered as the most promising scheme. The reasons are related to the structure of modern burners, and the flexibility in selecting the injection location. In this project, we have finally developed an active combustion control system using secondary fuel injection (Tachibana *et al.*, 2005).

Figure 13 shows a schematic of the combustion test rig. The rig is composed of an air supply system, an electric heater, a fuel-air mixing chamber and a combustion chamber. The fuel and air are supposed to be well mixed at the inlet. Methane is used as both for main and secondary fuels. The design concept is based on the idea that the stability of the global flame is greatly governed by the stability of the flame base. At operating conditions, the inlet air temperature and nominal velocity at the swirler are set to be 700 K and 90 m/s, respectively. The equivalence ratio ranges from 0.43 to 0.65, and this corresponds to the range of adiabatic flame temperature from 1660 to 2040 K.

A high-bandwidth electromagnetic directly-driven proportional valve (MOOG D633) is installed in the secondary fuel line so as to impose variations to the flow rate. A pressure transducer (Kulite

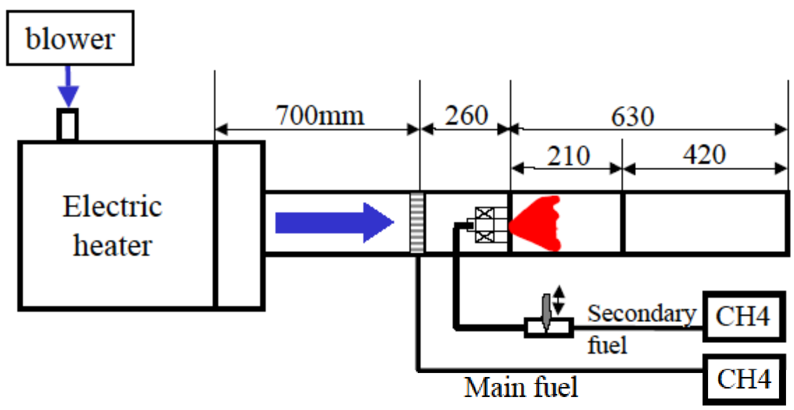

Fig. 13 Combustion test rig.

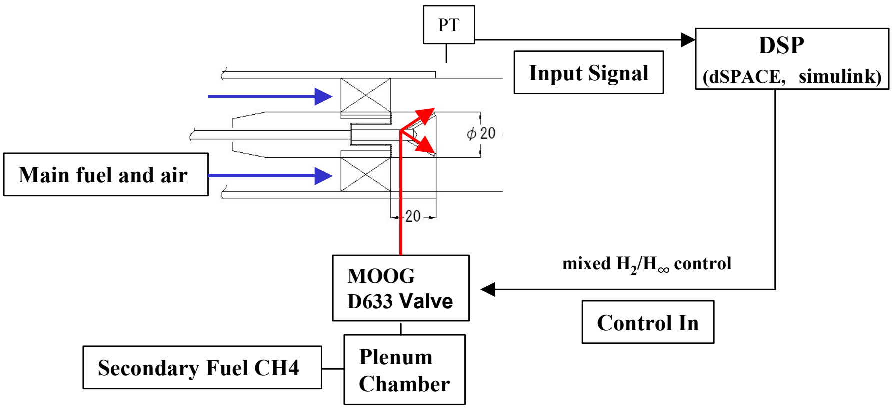

Fig. 14 Control system configuration.

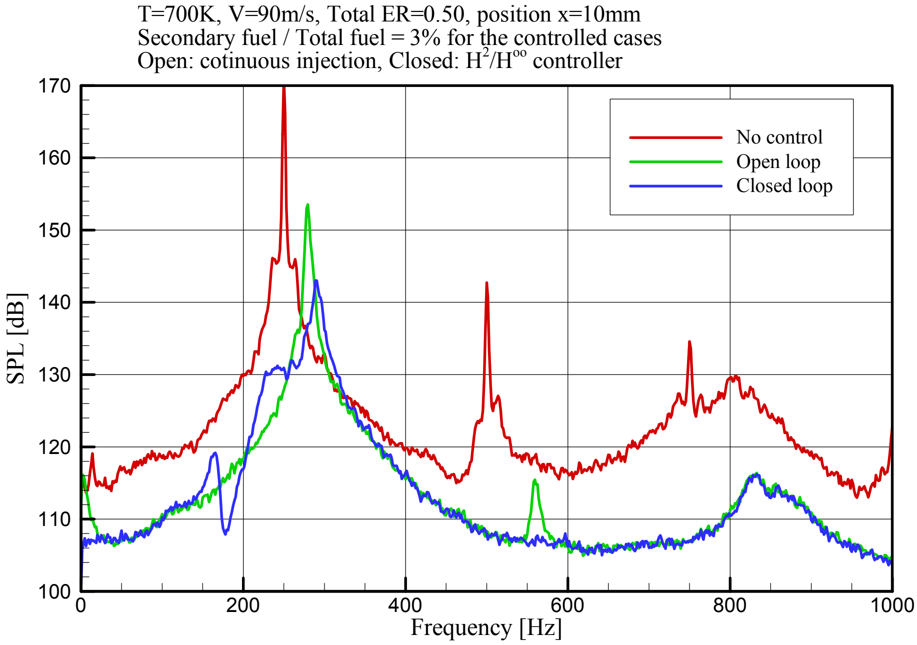

Fig. 15 Effect of control on pressure oscillations.

Semiconductor Products, Inc., Model XTL-190-15G) is used as the sensor. The signal from the sensor is connected to the controller. The mixed H_2/H_∞ controller developed by AGU (Sato *et al.*, 2004) and NMRI (Harumi *et al.*, 2003) is implemented and the output signal is sent to the MOOG valve as a command signal as shown in Fig. 14.

The controller successfully suppresses the combustion oscillation, while the phase in the identified model represents that of the combustion system only within the narrow frequency region. Better control performance is expected with the improvement of the system identification. The closed loop control is performed under the same conditions (T = 700 K, V = 90 m/s, ER_{total} = 0.50). The mean flow rate of secondary fuel is set at 3% of the total fuel flow rate. As seen in Fig. 15, this open loop control gives 17 dB reduction in peak Sound Pressure Level (SPL). Applying the closed loop, additional 10 dB reduction (28 dB in total) is achieved while keeping NOx emission within 5ppm.

5. Conclusions and remaining issues

The collaborative research project on "Smart Control of Turbulence: A Millennium Challenge for Innovative Thermal and Fluids Systems" has made continuous progress and several major breakthroughs during the last five years. It was a unique interdisciplinary research effort with a variety of researchers involved from national laboratories, universities and industries. The approach taken was theoretical, numerical and also experimental with emerging technology of MEMS, and these research methodologies themselves have been greatly advanced. The control targets were skin friction reduction, flow separation retardation and lean-mixed combustion stabilization. Each of the accomplishments is summarized below.

We demonstrated the effectiveness of active feedback control strategy for wall turbulence in a laboratory experiment for the first time by using a large-scale integrated control system. A prototype of fully MEMS-made system was also presented. Many issues are still remaining toward the use of such systems in real applications. Especially, further downsizing of sensors and actuators, development of actuators with a low power consumption, and invention of ground-breaking control algorithms are the essential issues.

A feedback control system for flow separation on an airfoil has been pursued. For this purpose, various new actuators and sensors are developed, *i.e.*, jet type vortex generator, flow direction discrimination sensor, and so on. By using those devices, a fundamental control system was proposed for the first time. However, each component composing the system is not necessarily optimized. Further optimization remains for future study, where the practical applications of the control system should be identified more clearly.

An advanced laser measurement facility for two phase flow was invented for diagnosis of turbulent bubbly channel flow. Detailed numerical simulation of moderately high Reynolds number bubbly flow was also made. In order to facilitate application to real systems, the bubble generation devices were devised, whilst model and full-scale ship tests were made for microbubble drag reduction. For the surfactant drag reduction, the heat transfer mechanism was studied and its enhancement was tested for the purpose of applying this technology to thermal energy transportation system.

An integrated combustion control system composed of sensor, actuator and regulating systems has been designed and installed in a methane lean premixed combustor with a swirler, aiming at the expansion of the stable range of combustion. In a final demonstration experiment, combustion instabilities were successfully suppressed by secondary fuel injection. As byproduct, important basic findings on combustion control are obtained for practical use in the future. Some of the major issues are control under higher pressure and temperature, robustness of the mixed H_2/H_∞ controller, and active control of horizontal mode instability in annular type combustors.

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