Temperature Field Measurement Around the Room Air Conditioner Using the LIF Technique*

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The spatial variations of temperature field around the room air conditioner model were measured using the LIF(Laser Induced Fluorescence) temperature field measurement technique. The room model and air conditioner model are scaled down by 1/20. And rhodamine B was used as a temperature indicator. The intensity variations of LIF signal from Rhodamine B excited by the laser light sheet were captured with an optical filter and CCD camera. Laser light sheet of an Nd-Yag laser illuminated a two-dimensional cross section of the discharge region of air conditioner. The true temperature field data were derived from the intensity information acquired from LIF temperature calibration. The measured results for propagation of heat and flow in the room model are discussed in this paper.

Key Words: Laser Induced Fluorescence, Room Air Conditioner, Temperature Field, Velocity Field, Particle Image Velocimetry, Rhodamine B

1. Introduction

Recently, in order to cope with the worsening of environmental problems, researches are being carried out in industrial fields to decrease energy consumption, including the field of home appliances. Summer household electricity consumption is greatly increasing due to the recent large home air conditioners. In order to reduce such increase in electricity consumption during the summer, the development of a high-efficiency air conditioner is needed, which in turn requires the development of a means to control the flow rate and direction of the cold air at the air conditioner discharge part. Therefore, the main objective of this study lies in the

accurate acquisition of flow velocity and temperature field data of the discharge part air flow through the use of PIV(Particle Image Velocimetry) and LIF(Laser Induced Fluorescence) techniques. The analyzed results will be used for the understanding of the flow mechanism and the development of the optimal discharge area geometry, along with a development of an effective algorithm for flow control.

Temperature measurements have been carried out through the pointwise measurement devices such as thermocouples and RTD(Resistance Temperature Detector) until the recent development of two-dimensional temperature field measurement techniques. These new techniques have been the more useful by the increased sensitivity of CCD(Charge Coupled Device) cameras and the development of optical and image processing systems. Recent developments in two-dimensional temperature field measurement techniques include LIF, holographic interferometry, and TLC(Thermochromic Liquid Crystal), which simultaneously incorporates optical and image processing systems for temperature field measurements.

* Recieved April 30, 2000

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These techniques are used for the analyses of acquired visualization images, and have the advantage of high accuracy due to the fact that the measurement method does not interfere with the fluid flow⁽¹⁾. TLC is widely used in simultaneous measurements of velocity and temperature fields as well as surface temperature field measurements, but the limited temperature measurement range and the non-homogeneous density distribution within the working fluid, and white-light scattering cause difficulties in accurate data acquisition.

However, LIF as a measurement technique with the application of a laser was initially used in spectroscopy and chemical analysis, such as density and temperature measurements of species including *OH*, *NO*, *CH*, and its largest application was lying in combustion analysis^{(2),(3)}. Recently however, its application extends to fluid flow, molecular ratios, density, velocity, and pressure visualization with the use of an ICCD(Intensified CCD) camera, and the measurement range is broadened to the room-temperature range. This measurement technique uses fluorescence, and has the advantage of having high spatial and spectral resolutions as well as a relatively simple measurement principle with easy data acquisition process and analysis.

In this study, the LIF technique was used for the analyses of the temperature diffusion characteristics of the cold air flow in a room model, along the PIV technique, which enables consecutive two-dimensional velocity field measurement, for the analyses of the flow characteristics.

2. Principle of LIF Technique for Temperature Measurement

The structure of an atom consists of the nucleus and the electrons spinning around the nucleus in a circular motion with unique energy levels at different excitation states for which each electron is allowed a single orbital path with a constant radius. The product of the momentum of the electron and the length of its orbital path are integral multiples of an arbitrary constant, and the energy value corresponding to such a quantum condition is called an energy state, which is unique for different atoms. The energy state of the dye molecule may be a *singlet*(*S*) or a *triplet*(*T*) according to the spin direction of the electrons. Energy states are vibrational-rotational energy levels, where the light absorption spectrum is wide and the absorption constant is large, therefore effectively making the transition to an excited state. Fluorescence is the light emission(*B*→*a* in Fig.1) when the

molecule undergoes a relaxation period of $10^{-9} \sim 10^{-8}$ sec after being excited to a *singlet*, and phosphorescence is the light emission when the molecule undergoes a similar relaxation transition from a triplet. LIF uses the former light emission, fluorescence.

Fig.1 Theory of fluorescence

The intensity of the fluorescence which emitted as a spontaneous emission(Fig.1 *B*→*a*) can be represented by the following equation,

$$S_F = \eta h \nu \frac{\Omega}{4\pi} V \frac{A_{21}}{A_{21} + Q_{21}} I \frac{B_{21}}{c} f_B N \quad (1)$$

- S_F : LIF intensity
- Q_{21} : collisional quenching rate
- f_B : population/Boltzmann fraction
- N : number density
- η : light collection efficiency
- h : Plank constant
- Ω : LIF collection solid angle
- V : measurement volume
- A_{21} : spontaneous emission coefficient.
- U : frequency of LIF
- B_{21} : stimulated emission coefficient
- c : light velocity
- I : excitation light intensity

Assuming atmospheric pressure in the measurement region is constant and the spontaneous emission constant A is negligible compared to the quenching rate Q , equation (1) can be represented as equation (2).

$$S_F = C \frac{1}{Q_{21}} f_B(T) N, \quad C = \eta h \nu \frac{\Omega}{4\pi} V A \frac{B}{c} I \quad (2)$$

The population density f is a function of temperature only, and the quenching rate Q is as

follows:

$$Q_{21} = C' \frac{p}{\sqrt{T}} = C' \frac{NkT}{\sqrt{T}} = C''N\sqrt{T} \quad (3)$$

p : pressure
 C' : constant
 k : Boltzman constant

In the above equation, uniform pressure distribution is assumed inside the measurement volume, then the LIF intensity is represented as follows,

$$\therefore S_f = C''' \frac{f_B(T)}{\sqrt{T}} \quad (4)$$

The LIF intensity can only be represented as a function of temperature only when constant pressure and density is assumed inside the measurement volume. The constant C''' is determined through calibration of the LIF intensity with temperature.

3. Measurement Apparatus

The LIF technique enables the temperature field measurements of both liquid and gas flow by proper selection of the dye according to the working fluid. Generally, rhodamine B is used for liquid working fluids due to its relatively high sensitivity (approximately 2%/K) to temperature. The absorption and emission spectrum of rhodamine B, as shown in Fig.2, has maximum absorption and emission at wavelengths of 540nm and 585nm respectively. With the use of an Nd:YAG laser (532nm), maximum absorption is possible, enabling sensitive light detection. Also, the

temperature measurement range is 70 °C at room temperature, being an advantage in liquid temperature measurements at room temperature.

Fig.2 Absorption and emission spectrum

In the case of temperature field measurements with gas as the working fluid, traditional fluorescent dyes have absorption bands in the ultraviolet region, therefore eximer or dye lasers must be used, or an Nd:YAG laser with a harmonic generator. Iodine however, can be used in the Ar-Ion wavelength range of 514.5nm, and the use of white visible light facilitates the setup of the optical system as well as intensifying the LIF signal.

Recently, experiments are carried out using two fluorescent dyes with laser-sheet scanning to obtain three-dimensional temperature distributions⁽⁴⁾. This method measures the temperature by calibrating the ratio of the LIF signals from the two dyes with the temperature. This method is favorable in reducing

Fig.3 Experimental setup

signal noise when the intensity of the laser is unreliable, or when the laser does not form a sheet of uniform intensity. Also, combining the LIF technique with PIV enables the simultaneous field measurement of the temperature and velocity.

4. Experiment

In this study, an LIF measurement system was developed for the temperature field measurement in the discharge region of an air-conditioner. Figure 3 shows the LIF system used in this study, consisting of rhodamine B, a B/W CCD camera with an Nd:YAG laser for image acquisition, an optical system to illuminate the two-dimensional measurement region, and an image processing system for the analysis of the acquired images. Rhodamine B was used as the fluorescent dye having a maximum absorption wavelength and maximum emission wavelengths of 540nm and 585nm, respectively.

Generally, the absorption and emission spectra overlap at certain wavelengths as can be seen in Fig. 2. It is favorable to position the laser wavelength that induces fluorescence below the emission spectrum and inside the absorption spectrum. An Nd:YAG laser was therefore used to excite the dye in the study. In order to accurately measure the temperature field, all signals must be filtered and only the fluorescence signal from the dye must be input to the camera. In other words, an optical filter which transmits only a particular wavelength is needed due to the fact that the signal from the laser that excite the dye acts as noise. Therefore, a 560nm orange filter was used to eliminate noise. Also, an ICCD camera should be used to compensate for the low light intensity, but a 300mJ/pulse high-power Nd:YAG laser was used in this study.

The room model was 406mm in length, 275mm in width, and 144mm in height, resulting in a 1/20 downscale of the environment chamber used for actual air-conditioner performance experiments. The discharge region of the air-conditioner model was downscaled as well to a size of 25mm in width and 16mm in height. Constant-temperature baths were used to supply water through the discharge region, and in order to maintain a constant pressure inside the room model, no resistance was given at the air-conditioner discharge region.

Velocity measurements were done through PIV, with the Nd:YAG laser and 100 μ m polymer seeding particles, and a two frame cross correlation algorithm to obtain velocity vector fields.

5. Result and Discussion

A calibration experiment for the fluorescent dye was carried out before actual measurements. The calibration was done by measuring the temperature with a thermocouple and acquiring the image of the test section with a CCD camera at the same time when the temperature inside the room model reached equilibrium with the water circulation from the constant temperature baths. The calibration range was 15 $^{\circ}$ C~65 $^{\circ}$ C and the intensity was normalized with the basis of 27 $^{\circ}$ C. The calibration result is shown in Fig.4. The R^2 (coefficient of determination) of the calibration curve fitting was 0.986, and the sensitivity to temperature was found to be approximately 2%/K at 25 $^{\circ}$ C.

Fig.4 Calibration curve

In order to understand the discharge distance of the jet in relation to the temperature difference, the jet structure was investigated according to the Ar number.

$$Ar = \frac{\beta \Delta T g L}{V^2} \quad (5)$$

β : thermal expansion coefficient

ΔT : difference of temperature

g : gravity

L : characteristic length

V : velocity

The Ar number is a dimensionless number used when natural convection and forced convection are in the same order of magnitude. Especially it is frequently used for non-isothermal flows in air conditioning model analogy. The flow rate and the temperature difference between the jet and the room

model were used as variable experimental parameters, with their values as shown in Table 1.

Table 1. Experimental parameter

Case	Ar	$\Delta T(^{\circ}C)$	$Q(lpm)$
Case 1	0.324	25	0.67
Case 2	0.195	15	0.67
Case 3	0.1	25	1.204
Case 4	0.06	15	1.204

Figure 6(a)~(d) represent the mean temperature field and velocity field of cases 1, 2, 3 and 4, respectively. The momentum and thermal diffusivities show some differences in all four cases, but a similarity in the jet center is observed in terms of momentum and thermal energy. This can be confirmed by the coinciding maximum velocity line(MVL) and minimum temperature line(MTL) in result of Fig.5. The maximum velocity line and the minimum temperature line are calculated from respective maximum and minimum points at perpendicular cross-sections of the jet. The MVL and the MTL may be considered as the maximum momentum line and the minimum heat energy line. Therefore, the control of air current would achieve an indirect control of the temperature distribution.

Also, according to the temperature distribution of Fig. 6, the jet width of the low Re (case 1, 2) is greater than that of the high Re (case 3,4) in the region immediately after the discharge. But these are gradually decreasing and the jet width of the high Re

case is becoming greater. This is considered to be due to the effect of high turbulence intensity on thermal diffusivity, resulting in a higher heat transfer rate to the surrounding fluid. Also, comparing the temperature variation along the MTL of case 1 and case 2, it can be observed that the result of case 1 maintains a lower heat energy for a longer period of time, which is considered to be due to the Re difference.

Fig. 5 Similarity of temperature and velocity

An inverse proportionality was found between the jet transfer distance and Ar from the result shown in Fig. 5. A large Ar value causes a large buoyancy effect, and causes a perpendicular force on the jet, therefore decreasing the transfer rate of the cold jet. The

Fig. 6 Flow pattern around the discharge part of air conditioner

transfer distance and the jet width can be controlled in this manner, by proper adjustments of Ar and Re values, enabling global cooling or local cooling in a room.

In order to observe the heat transfer characteristics due to a locally non-uniform temperature jet, the jet flow characteristics in a relatively local region were studied. Figure 7(a) shows the instantaneous temperature field at $Re=2294$ and $\Delta T=15^\circ\text{C}$, which shows a stable laminar flow in the vicinity of the discharge region and a distinct vortex in the downstream region due to the effect of the still surrounding fluid. Nearly no heat transfer occurs in the beginning of the jet except in the vortex region while most of the heat transfer occurs centered in the vortex at downstream locations, in addition to the very small thermal diffusivity in most regions. The width of the low Re jet showed a decreasing trend according to the instantaneous temperature field.

(a)

(b)

Fig.7 Instantaneous temperature distribution

Figure 7(b) shows the instantaneous temperature

field at $Re=4246$ and $\Delta T=15^\circ\text{C}$. A fully turbulent flow is found at the discharge region, and a high heat transfer rate is found along the jet due to flow fluctuations, especially due to small eddy motions. In comparison with Fig. 7(a), the transfer distance is shorter for the lower temperature, while the flow width increases due to large momentum dissipation and thermal diffusivity as the flow goes downstream. This is identical to the *coherent structure* forming at the interface of a turbulent fluid and non-turbulent fluid.

6. Conclusion

Thermal energy and momentum dissipation mechanisms were studied by the application of LIF for temperature field measurements and PIV for velocity field measurements in a non-uniform temperature discharge jet of a scaled-down air-conditioner model. The LIF technique was confirmed to be an effective method in temperature field measurement. The Re number was found to be the dominant factor affecting thermal diffusivity of the discharge flow due to its effect on momentum diffusivity, and that the jet transfer distance is determined by the Ar number, which is the ratio of buoyancy to momentum. Also, by analyzing the local heat transfer characteristics in the jet, important heat transfer mechanisms between laminar and turbulent flows were found. The temperature and velocity field measurements carried out in this study are expected to support the development of flow control algorithms for air conditioner discharge regions as well as the future flow control algorithms.

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