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FINAL REPORT
ON
HEAT TRANSFER IN OSCILLATORY FLOW

by

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I. DESCRIPTION OF RESEARCH ACCOMPLISHMENTS

1. Introduction

This is the final report on a 4-year research effort funded by DOE. THe bulk of the material has been included in numerous publications which are listed in a later section. Most of these have appeared already in archival journals. The most recent work is included in two Ph.D. dissertations. Reprints and manuscripts are submitted together with this report.*

Since most of the material is already documented in detail in the publications mentioned above, we confine the discussion here to highlights of the results.

2. Literature Review

The problem of hydrodynamic interference between circular cylinders is a fundamental problem which also has immediate application in a variety of engineering designs. Interference between a few cylinders is encountered in flow across piles or pipes, whereas interference between a larger number of more closely packed cylinders is found in heat exchangers. The problem is quite complex because it involves interaction between different scales of turbulence, mainly the scales of the attached boundary layers and the large-scale structures generated by vortex shedding. The fluid flow behavior is also intimately connected with heat transfer. A good number of experimental studies have been reported on configurations of 2, 3 or 4 cylinders in a row. However, no attempt has been made so far to study the effect of freestream pulsation on the organization of the wakes and the heat transfer. This is the topic of the present research.

* Cycled separately -

The unsteady problem of the flow and heat transfer over a single cylinder has received a lot of attention recently. Lebouche and Martin [1] measured local heat and mass transfer for pulsating flow in the range $15000 < Re < 50000$. For their mass transfer studies, the pulsation frequency was varied up to 86 percent of the natural vortex shedding frequency with amplitudes of up to 32 percent. At a ratio of the driving to the shedding frequency, $f_d/f_s = .43$ and an amplitude of 36 percent, they reported no increase in heat transfer on the front and a 31 percent increase on the back of the cylinder. Borell et al. [2] used a local heat flux gage to investigate the effect of pulsating flow on the heat transfer distribution over a single cylinder for $33000 < Re < 66000$. Well-organized sinusoidal pulsations were used both below and above the natural shedding frequency. They reported increases in local heat transfer near the separation point, which were largest near $f_d/f_s = 1$. No increase outside of experimental error was observed for the overall heat transfer. Kim et al. [3] solved numerically the unsteady boundary layer equations on the front of the cylinder. For a 10 percent oscillation in velocity at the edge of the boundary layer, they reported about a 3% increase in heat transfer at the front stagnation point, and a small decrease upstream of the separation point. Andraka [4] extended Borrell's investigation, producing more accurate results at $Re = 50000$ with a larger cylinder ($D = 8.89$ cm) and lower tunnel blockage. Pulsations were reported to have no effect on the time-averaged heat transfer except near the separation point. However these findings were later contradicted by VandenBerge [5] who found increases of heat transfer in the wake region of the cylinder. In these experiments it was demonstrated that the heat transfer increases monotonically with frequency through the natural shedding frequency.

The steady flow and heat transfer over in-line cylinders have also been investigated recently. Kostic and Oka [6] investigated constant-heat-flux heat transfer and fluid flow around a tandem arrangement of two cylinders at subcritical Reynolds numbers. They suggest three flow regimes based on pitch ratio, namely the ratio of the spacing L to the diameter D. Hiwada et al. [7] measured mass transfer and fluid flow around a tandem arrangement of two cylinders, and reported similar local mass transfer distributions as those presented by Kostic and Oka for heat transfer. They disagreed, however, over the interpretation of the flow around the cylinders. Hiwada et al. also reported on a discontinuity in Strouhal number, at the beginning of the closed vortex formation region (L/D = 3.8). Zdravkovich [8] reviewed studies of flow interference between two circular cylinders. He suggested that no vortex shedding exists behind the first cylinder at spacings below L/D = 3.8, where the jump phenomenon occurs, and that at L/D = 3.8, two values of Strouhal number exist intermittently. More recently, a second discontinuity has been observed both in heat transfer and Strouhal number measurements for spacings smaller than L/D = 3.8. This second jump phenomenon is dependent on both Reynolds number and L/D [9,10].

No constant-wall-temperature (CWT) heat transfer data was found for in-line arrangements of three cylinders. Aiba et al. [9-11] reported on the second cylinder in three and four cylinder arrangements for a constant-heat-flux (CHF) boundary condition. Igarashi [10] characterized the flow around three cylinders based on instantaneous and time-averaged flow visualizations along with pressure, velocity, drag and shedding frequency measurements. We report first on our investigation on steady flow and CWT heat transfer over a triad of cylinders. The results are compared with earlier data. We then discuss the extension of the work to unsteady flow and compare mean quantities with their corresponding steady-flow counterparts.

3. Experimental Arrangement

Tests were conducted in a wind tunnel and a water tunnel. Triads of cylinders were positioned in the test sections, as shown schematically in Fig. 1. The spacing of the cylinders L/D (see Fig. 1 for notation) was varied from 1.1 to 4.75. In most unsteady tunnels, adjustments of the frequency affect the amplitude of the oscillation. A unique feature of the tunnels employed in this investigation is the ability to control independently the amplitude and the frequency of the freestream oscillation. It should also be emphasized that other basic characteristics like uniformity of flow, turbulence level, and waveform of the periodic disturbance are features which are coupled. Improvement of one characteristic often affects unfavorably another. All of these quantities have been carefully documented, including the turbulence length scales and intensity and the organization of the externally imposed perturbation. Calibration data, description of the facility capabilities, and the ranges of the parameters that can be achieved are provided in earlier publications [4,5,12,13].

In the wind tunnel hot-wire and hot-film probes were used to monitor the flow field around the models. Pressure transducers and sensitive microphones were employed to record the mean and fluctuating pressure, respectively, and skin-friction gauges were used to measure instantaneous values of shear stresses on the wall. An instrumented model was constructed to measure simultaneously skin friction and pressure along a generator of the cylinder. The model was rotated by a stepping motor to allow proper positioning of the sensors and measurements at different azimuthal positions.

The test cylinder was a thick-walled copper tube, cut lengthwise into four quarter segments. Each segment was independently heated and insulated from surrounding cylinder segments. Guard heaters were placed at either end of the cylinder to reduce end losses. Automatic temperature controllers were used to maintain each cylinder segment at a constant and matched temperature to within ± 0.1° C. Heat transfer for each segment was determined by measuring the electric power supplied to each heater. Temperature on each segment was determined by averaging 5 thermocouples mounted flush on its surface. The combined effect of corrections made for radiation and for heat lost in the insulation was no larger than 2 percent. The cylinder model was positioned in the tunnel to measure heat transfer on the front and back segments of the cylinder. Experimental uncertainty was estimated to be 2.7% for the entire cylinder, and 3.1% for a cylinder half section. The skin friction gauge was calibrated on the model on which it was mounted. This was achieved by taking data at $\theta = 10°$ and $\theta = 30°$ for a range of velocities. The reduced readings were then contrasted against earlier experimental data, as well as our own calculations. A 4th degree polynomial was passed through the experimental points. This calibration curve was then employed to convert the voltage output to reduced skin friction values.

4. The Flow Field

Extensive flow visualization studies have been conducted in the water tunnel. Flow was visualized in terms of particles, dyes, or a combination of both particles and dyes. Time exposure of particles generate small segments which are essentially particle paths and therefore approximately parallel to the velocity vectors. The dyes on the other hand generate streaklines.

Our visualization studies indicated that the region between the first and the second cylinder contains two standing vortices. The flow in this region therefore resembles cavity flow. However, violent vortex shedding occurs over the second cylinder. The asymmetry created by this shedding process induces a periodic disturbance in the flow over the first gap. As a result, there is periodic spillover of the fluid contained in the first gap. The violent shedding over the second, or rather over the first 2 cylinders turns the flow sharply and attaches it periodically on the third cylinder. Moreover, the freestream is directed periodically between the second and third cylinder. An instantaneous particle visualization is shown in Fig. 2.

Wake flows as well as cavity flows contain random and organized elements. The organization usually consists of large-scale structures and is due to the rolling up of free-shear layers which emanate from separations. The organized motion is bound to bring into the wake or cavity freestream fluid. As a result, an increase in the organization in such flows should result in an increase in the heat transfer. Our hypothesis in this investigation has been that the degree of organization in wake and cavity flows can be increased by pulsing of the oncoming freestream at frequencies that induce lock-on. Moreover, it is believed that an increase of the turbulent energy implies more active flows and should also result in increased heat transfer. The level of activity in the wake or cavity can be estimated by inspecting frequency spectra of skin friction and velocity measurements.

A very large number of data were obtained over the second cylinder for steady and unsteady flow and will be included in an Engineering Report. For a spacing of L/D = 1.1, we display in Fig. 3 the RMS of the skin friction fluctuations for steady as well as pulsed flow. The behavior of the mean shear - not shown here - is qualitatively almost identical. For pulsed flow, increased activity can be found in the front part, where indeed the heat transfer was measured to be higher, as discussed in the next section.

The natural shedding is less violent for smaller spacings, but it takes smaller amplitudes for this shedding process to lock on a disturbance. Moreover, the shedding characteristics are more suppressed in the cavities between the cylinders as the spacing L/D decreases. For example, for the smallest spacing tested, namely L/D = 1.1 and for a Reynolds number Re = 25,000, the Strouhal frequency is f_{so} = 11.5 Hz. Pulsing the flow at f_D = 18.7 Hz caused the natural shedding frequency to shift and lock on the subharmonic of the driving frequency, namely f_s = 9.4 Hz. This is clearly shown in Fig. 4, where the frequency spectrum of hot wire measurements in the wake of the triad of cylinders is displayed. The organization of the cavity flows was studied by virtue of skin friction and surface pressure measurements along many azimuthal locations. Typical results are displayed in Figs. 5 and 6 for θ = 40° and 140° respectively. In these figures, the natural frequency and its harmonic can be detected clearly only in the pressure spectra. It is interesting to note in the same figures that when the flow is disturbed, the natural-shedding peaks are reduced. More importantly, for unsteady flow, clear and well pronounced spikes appear in the skin friction spectra. This betrays a more organized recirculating motion and therefore the possibility of increased heat transfer. The overall level of turbulence is also increased in both the cavities and this should result again in increased heat transfer rates. This is the topic of the discussion of the following section.

5. Heat Transfer

Heat transfer measurements were conducted on the second cylinder of an in-line arrangement with varying pitch ratio from 1 to 4.5, frequency from zero to 23 Hz, and at Reynolds numbers of 23,000 and 48,000. For steady flow, overall heat transfer on the second cylinder is 20 to 25 percent higher than for a single cylinder. When freestream pulsations were added, consistent increases in heat transfer of up to 12 percent were observed on the front of the cylinder. Small increases were also seen on the back, however, these increases were within the experimental uncertainty of measurement. Increases were largest (a) at lower Reynolds number (Re = 23,000), (b) at smaller spacings and (c) at higher frequencies. Figure 7 shows the increase in Nusselt number per unit amplitude of pulsation (τ) for different spacings and pulsation frequencies.

The present experimental data indicate that the shedding over multiple cylinders can be captured more easily by external disturbances than the shedding over a single cylinder. Such wake-capture or lock-on induces an increase of the organization in the wakes or cavities. Moderate increases of the heat transfer were achieved by pulsing the flow over the instrumented cylinder. Such increases were found to be more pronounced for higher frequencies, although the experimental apparatus did not permit tests much beyond twice the natural shedding frequency. These increases were larger on the front of the cylinder, which is contained in the cavity of the first two cylinders. The effect depends on the spacing of the cylinders, L/D, and decreases as L/D increases.

6. Analysis

The parallel computational effort was 3-pronged. The first prong was directed at the development of the unsteady boundary layer and the heat transfer on the attached region of the flow. This approach was based on finite-difference solutions of parabolic equations. The most significant results appear in Ref. 14.

In the second prong we employed the full Navier-Stokes equations in order to capture the entire flow field including the separated regions for flows over rows and bundles of cylinders. This approach was based on a finite-element method. Typical results are shown in Figs. 8 and 9. Figure 8 displays the isotherms, isobars and isovorticity lines for a five-row deep bundle of cylinders. Characteristic bulges in the pressure distributions betray the neighborhood of reattaching regions. The corresponding heat transfer distribution is shown in Fig. 10. More details the reader will find in Refs. 15 and 16.

The third analytical effort was the development of a model of the wake-region heat transfer based on the time-resolved measurements [17]. The measurements demonstrated a strong coherent structure at multiples of the vortex shedding frequency, as shown in Fig. 10. The vortex shedding process was modeled as an impinging jet that oscillates with time past the rear stagnation point of the cylinder. This provides a time-dependent distribution of heat transfer over the rear portion of the cylinder. It matches well with the experimental measurements of the phase and amplitude of the heat transfer oscillation and with the measured time-averaged heat transfer distribution. An example is shown in Fig. 11. It also predicts well the increased heat transfer measured due to flow pulsation.

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3. Kim, B. K., VandenBrink, D. J., Cramer, M. S., and Telionis, D. P., "Unsteady Heat Convection Over Circular Cylinders," ASME Paper No. 84-HT-100, 1984.

4. Andraka, C. E. and Diller, T. E., "Heat Transfer Distribution Around a Cylinder in Pulsating Crossflow," ASME J. of Engineering for Gas Turbines and Power, Vol. 107, 1985, pp. 976-982.

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8. Zdravkovich, M. M., "Review of Flow Interference Between Two Circular Cylinders in Various Arrangements," ASME J. of Fluids Engineering, 1977, pp. 618-633.

9. Aiba, S., Ota, T. and Tsuchida, H., "Heat Transfer of Tubes Closely Spaced in an Inclined Bank," International Journal of Heat and Mass Transfer, Vol. 23, 1980, pp. 311-319.

10. Igarashi, T., and Suzuki, K., "Characteristics of Flow Around Three Circular Cylinders Arranged in Line," Bulletin of the JSME, Vol. 27, No. 233, Nov. 1984, pp. 2397-2404.

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12. Tavakoli, A., Kim, B. K., Borell, G. J., Diller, T. E. and Telionis, D. P., "Design and Evaluation of a Pulsating-Flow Wind Tunnel," VPI & SU, Engineering Report No. VPI-E-83-41, May 1983.

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14. Kim, B. K., VandenBrink, D. J., Cramer, M. S. and Telionis, D. P., "Unsteady Heat Convection Over Circular Cylinders," ASME Paper No. 84 HT-100, 1984, presented at the ASME/AIChE National Heat Transfer Conference, Niagara Falls, Aug. 6-8, 1984, also AIChE Journal, in press.

15. Dhaubhadel, M. N., Reddy, J. N. and Telionis, D. P., "Penalty-Finite-Element Analysis Coupled Fluid Flow and Heat Transfer Over In-Line Bundle of Cylinders in Cross Flow", International Journal of Nonlinear Mechanics, Vol.21, 1986, pp. 361-373.

16. Dhaubhadel, M. N., Reddy, J. N. and Telionis, D. P., "Finite-Element Analysis of Fluid Flow and Heat Transfer for Staggered Bundle of Cylinders in Cross Flow", accepted for publications in the International Journal for Numerical Methods in Fluids.

17. Gundappa, M. and Diller, T. E., "Unsteady Heat Transfer Measurements Around a Cylinder in a Pulsating Cross Flow", accepted for the ASME/JSME Thermal Engineering Conference, Hawaii, March 1987.

II. PUBLICATIONS

II.1. Senior Projects

II.1.1 "Pressure Variations About a Circular Cylinder in Pulsating Cross Flow" by William Ekhaml, ESM Senior Project Report, May 1984.

II.1.2 "The Use of Liquid Crystal Composites as a Visual Medium for the Qualitative and Quantitative Determination of Local Heat Transfer Coefficients", by Robert Swain III, ESM Senior Project Report, May 1985.

II.1.3 "Vortex Shedding Frequencies of Three Cylinders in a Cross Flow", by A. B. Russel, ESM Senior Project Report, May 1985.

II.1.4 "Skin Friction Measurements Over In-Line Cylinders in Pulsating Flow," by Andrew Hetz, ESM Senior Project Report, expected Summer 1986.

II.2. M.S. Theses

II.2.1 "Design and Evaluation of a Pulsating Flow Wind Tunnel", VPI & SU, M.S. Thesis by Amir Tavakoli, October 1982.

II.2.2 "Heat Transfer from a Circular Cylinder in a Pulsating Cross-Flow", VPI & SU, M.S. Thesis by George J. Borell, October 1983.

II.2.3 "Heat Transfer from a Cylinder in Oscillating Crossflow," VPI & SU, M.S. Thesis by Charles E. Andraka, August 1984.

II.2.4 "Design and Calibration of a Rapid-Response Thin-Film Heat Flux Gage", VPI & SU M.S. Thesis by David S. Campbell, Feb. 1985.

II.2.5 "Heat Transfer from In-Line and Perpendicular Arrangements of Cylinders in Steady and Pulsating Crossflow," VPI & SU, M.S. Thesis by Terrance M. VanderBerghe, Sept. 1985.

II.3 Ph.D. Dissertations

II.3.1 "Steady and Pulsating Flow Over a Circular Cylinder," VPI & SU, Ph.D. Dissertation, by B. K. Kim, December 1984.

II.3.2 "Fluid Flow and Heat Transfer Over Multiple Cylinders in Pulsating Flow - Theory & Experiment," VPI & SU, Ph.D. Dissertation, by M. Dhaubhadel, August 1986.

II.3.3 "Time-Resolved Heat Transfer Measurements and Analysis in the Wake Region of a Cylinder in Crossflow," VPI & SU, Ph.D. Dissertation, by M. Gundappa, expected Winter 1987.

II.4 Engineering Reports

II.4.1 "Design and Evaluation of a Pulsating-Flow Wind Tunnel" by A. Tavakoli, B. K. Kim, G. J. Borell, T. E. Diller and D. P. Telionis, VPI & SU, Engineering Report No. VPI-E-83-41, May 1983.

II.4.2 "Calibration of the ESM Water Tunnel", by D. P. Telionis, D. Mathioulakis, B. K. Kim and G. S. Jones, VPI & SU, Engineering Report No. VPI-E-86-23, November 1986.

II.5 Papers

Note: Papers that have appeared or are accepted for publication in archival journals are marked by the symbol.*

Papers that were presented at a conference but were reviewed in full length by two or more reviewers are marked by the symbol ‡.

II.5.1 "Pulsating Flow & Heat Transfer Over a Circular Cylinder", by B. K. Kim, G. J. Borell, T. E. Diller, M. S. Cramer and D. P. Telionis, in DOE CONF-830413, pp. 96-101, Presented at the Symposium on Nonlinear Problems in Energy Engineering, Argonne National Laboratory, April 1983.

‡ II.5.2 "Pressure and Heat Transfer Measurements Around a Cylinder in Pulsating Crossflow," by G. J. Borell, B. K. Kim, Ekhaml, T. E. Diller and D. P. Telionis, in Unsteady Turbulent Boundary Layers and Friction, Eds. D. C. Wiggert and C. S. Martin, ASME, 1984, pp. 17-23, presented at ASME Fluids Engineering Conference, New Orleans, Feb. 1984.

*‡ II.5.3 "A Convection Calibration Method for Local Heat Flux Gages," by G. J. Borell and T. E. Diller, ASME Paper No. 84-HT-45, 1984, presented at the ASME/AICHE National Heat Transfer Conference, Niagara Falls, Aug. 6-8, 1984, ASME Journal of Heat Transfer, in press.

*‡ II.5.4 "Unsteady Heat Convection Over Circular Cylinders," by B. K. Kim, D. J. VandenBrink, M. S. Cramer and D. P. Telionis, ASME Paper No. 84 HT-100, 1984, presented at the ASME/AICHE National Heat Transfer Conference, Niagara Falls, Aug. 6-8, 1984, also AIChE Journal, in press.

*‡ II.5.5 "Heat Transfer Distribution Around a Cylinder in Pulsating Crossflow," by C. E. Andraka and T. E. Diller, ASME Paper No. 85-GT-67, presented at the 30th ASME International Gas Turbine Conference, Houston, March 1985, also ASME J. of Engineering for Gas Turbines & Power, Vol. 107, 1985, pp. 976-982.

‡ II.5.6 "Design and Calibration of a Local Heat-Flux Measurement System for Unsteady Flows," by D. S. Campbell and T. E. Diller, in Fundamentals of Forced & Mixed Correction, Eds. F. A. Kulacki and R. D. Boyd, ASME, pp. 73-80, presented at the 23rd National Heat Transfer Conference, Denver, Aug. 1985, also submitted for publication in ASME Journal of Heat Transfer.

II.5.7 "The Effect of Polymer Additives on Laminar Separation," by B. K. Kim and D. P. Telionis, presented at the XVII Biennial Fluid Mechanics Symposium, Sobieszewo, Poland, Sept. 1985, also submitted for publication in the Physics of Fluids.

‡ II.5.8 "The Effects of Freestream Turbulence and Flow Pulsation on Heat Transfer from a Cylinder in Crossflow," by M. Gundappa and T. E. Diller, in Augmentation of Heat Transfer in Energy System, Ed. P. J. Bishop, ASME, pp. 29-36, also presented at the ASME WAM, Miami, Nov. 1985.

*‡ II.5.9 "Heat Transfer in a Perpendicular Arrangment of Cylinders in Steady and Pulsating Crossflow," by T. VandenBerghe and T. E. Diller, presented at the Eighth International Heat Transfer Conference, San Francisco, Aug. 17-22, 1986. Also Heat Transfer 1986, Vol. 3, Eds. C. L. Tien et al., Hemisphere Pub. Corp., NY, 1986, pp. 1029-1034.

II.5.10 "Periodic Flow and Heat Transfer Over Multiple Cylinders," by D. P. Telionis and T. E. Diller, presented at the Third Symposium on Energy Engineering Sciences, Penn. State Univ., University Park, PA, October 1985.

* II.5.11 "Vortex Shedding and Lock-On of a Circular Cylinder in Oscillatory Flow," by C. Barbi, D. P. Favier, C. A. Maresca, and D. P. Telionis, Journal of Fluid Mechanics, Vol. 170, 1986, pp. 527-544.

* II.5.12 "Penalty-Finite-Element Analysis Coupled Fluid Flow and Heat Transfer Over In-Line Bundle of Cylinders in Cross Flow," by M. N. Dhaubhadel, J. N. Reddy, and D. P. Telionis, International Journal of Nonlinear Mechanics, Vol. 21, 1986, pp. 361-373.

‡ II.5.13 "Momentum, Heat and Mass Transfer in Two-Dimensional Laminar Boundary-Layer Flow of Power-Law Non-Newtonian Fluids," by B. K. Kim, D. P. Telionis, and M. S. Cramer, World Congress III of Chemical Engineering, Tokyo, Japan, Vol. 7, 1986, pp. 336-339.

‡ II.5.14 "The LDV Measurements of Polymer-Aided Drag-Reducing Flow Over a Circular Cylinder in Cross Flow," by B. K. Kim and D. P. Telionis, World Congress III of Chemical Engineering, Tokyo, Japan, Vol. 7, 1986, pp. 222-225.

‡ II.5.15 "Natural and Forced Hydrodynamic Oscillation of Cylinder Bundles," by B. K. Kim, M. N. Dhaubhadel, and D. P. Telionis, Third International Conference on Computational Methods and Experimental Measurements, Ed. Keramidas, G. A. and Brebia, C. A., Vol. 2, 1986, pp. 787-800.

‡ II.5.16 "Unsteady Heat Transfer Measurements Around a Cylinder in a Pulsating Cross Flow," by M. Gundappa and T. E. Diller, accepted for the ASME/JSME Thermal Engineering Conference, Hawaii, March 1987.

* II.5.17 "Finite-Element Analysis of Fluid Flow and Heat Transfer for Staggered Bundle of Cylinders in Cross Flow", by M. N. Dhaubhadel, J. N. Reddy and D. P. Telionis, accepted for publication in the International Journal for Numerical Methods in Fluids.

III. PERSONNEL

III.1 Engineering Science & Mechanics

Messrs. Cramer, Kim, Dhaubhadel, and Telionis have participated in this project. They have worked on the analytical as well as the experimental effort. In the water tunnel work, Mr. Costis has been providing some assistance on a part-time basis in the development of data acquisition software. Moreover, Mr. Ekhaml has participated in the calibration of B&K microphones and the collection of unsteady pressure data in the wind tunnel.

Mr. Ekhaml has completed a senior project and graduated in December 1983. Ms. Swain has also participated developing a parallel method based on liquid crystals for his senior project and graduated in June 1985.

Messrs. Kim and Dhaubhadel worked on their Ph.D. dissertations and defended successfully in December 1984 and August 1986, respectively. The first has developed boundary-layer finite-difference codes, while the second worked on a finite-element, Navier-Stokes solver. Both participated in the experimental work as well. Mr. Kim is now an Associate Professor at the University of Ulsan in Korea, while Mr. Dhaubhadel is spending a year at VPI & SU also as an Assistant Professor.

II.2 Mechanical Engineering

Messrs. Tavakoli, Borell, Andraka, Campbell, VandenBerghe, Gundappa and Diller have participated in the research. Mr. Tavakoli developed the first pulsating wind tunnel. He graduated in 1982 and went to work for Fairchild Corp.

Mr. Borell graduated in September, 1983, with a Master's Degree and is currently working for the Harris Corporation. He was responsible for the heat transfer measurements and development of the heat flux calibration system.

Mr. Andraka also held an NSF fellowship while working on the project. After graduating in 1984, he took a job at Sandia National Laboratory.

Mr. Campbell began work on the unsteady heat flux measurement system. He completed his thesis in 1984 and began working for TRW.

Mr. VanderBerghe designed and built the surface average heat transfer system. After graduating in 1985, he travelled extensively in Europe before looking for a job in the U.S.

Mr. Gundappa performed extensive work on the time-resolved local heat transfer. He is expected to defend his Ph.D. work in January 1987 and has accepted a postdoctural position at VPI & SU.

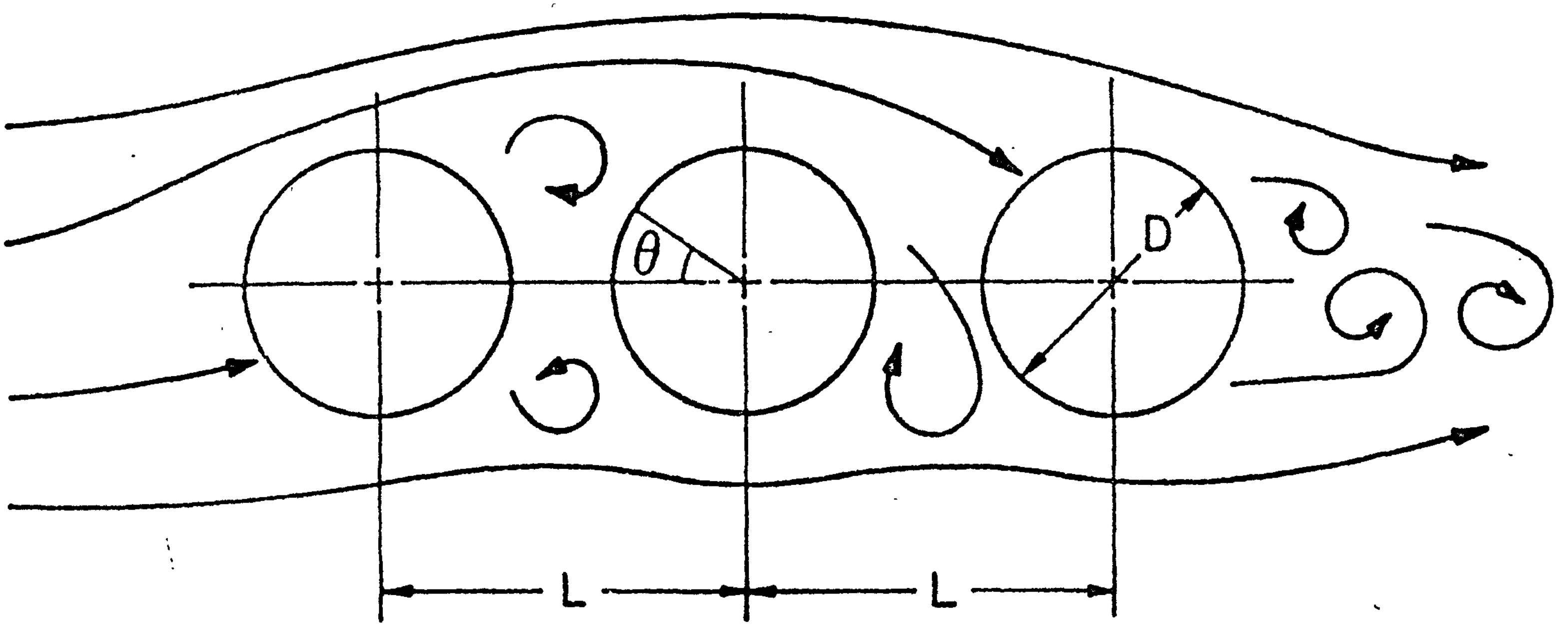


Fig. 1 Schematic representation of the flowfield.

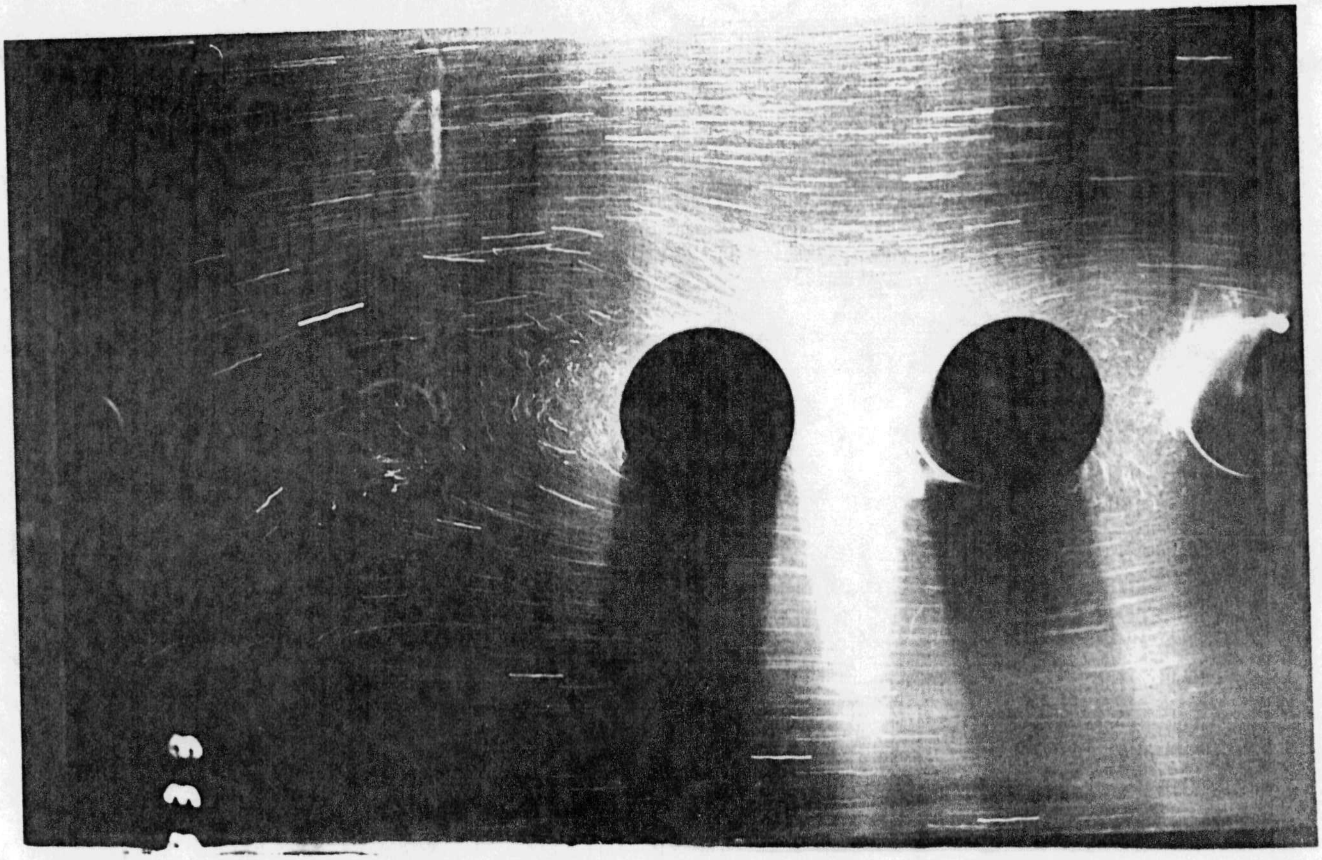


Fig. 2 Particle flow visualization of the flowfield.

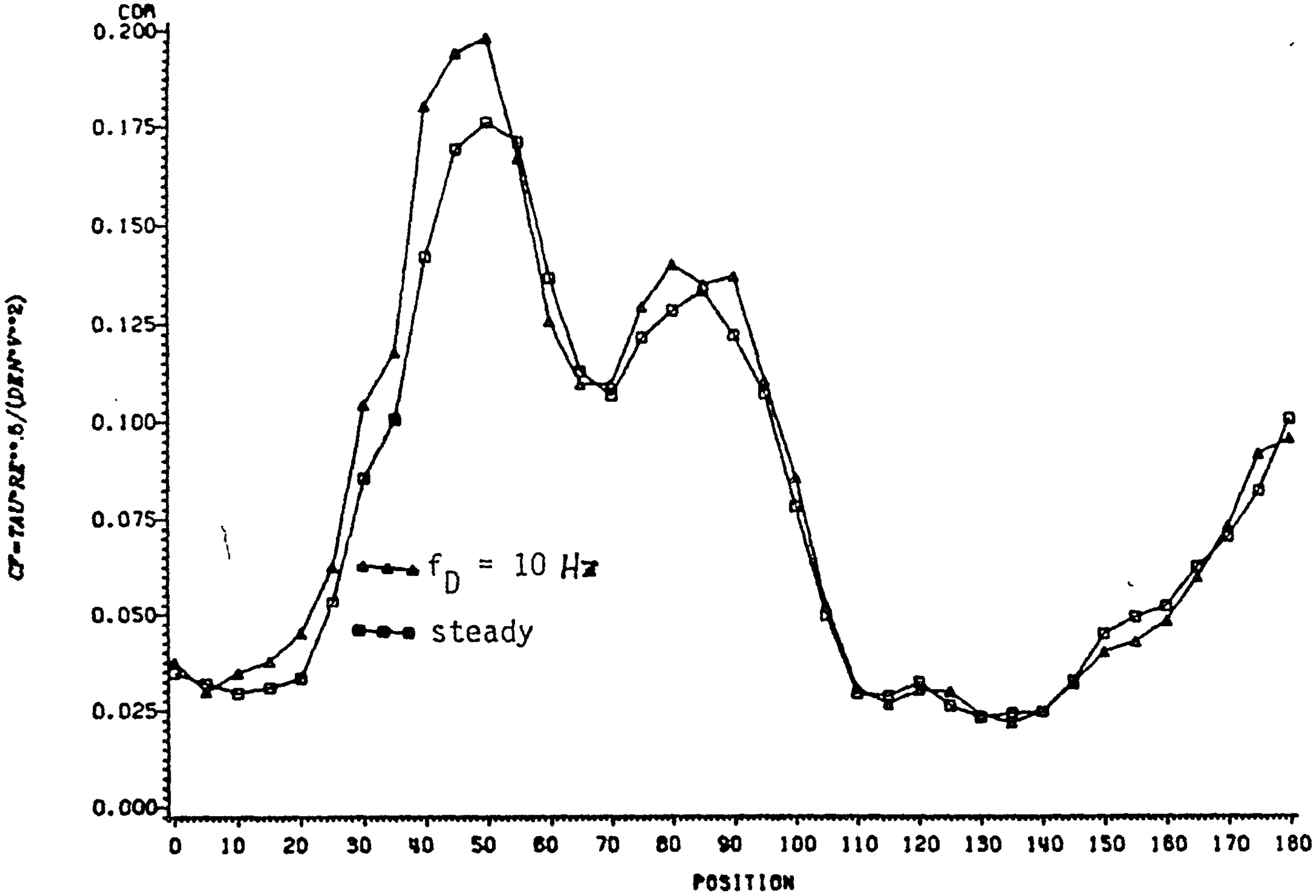


Fig. 3 RMS of the skin friction over the middle cylinder for L/D = 1.1.

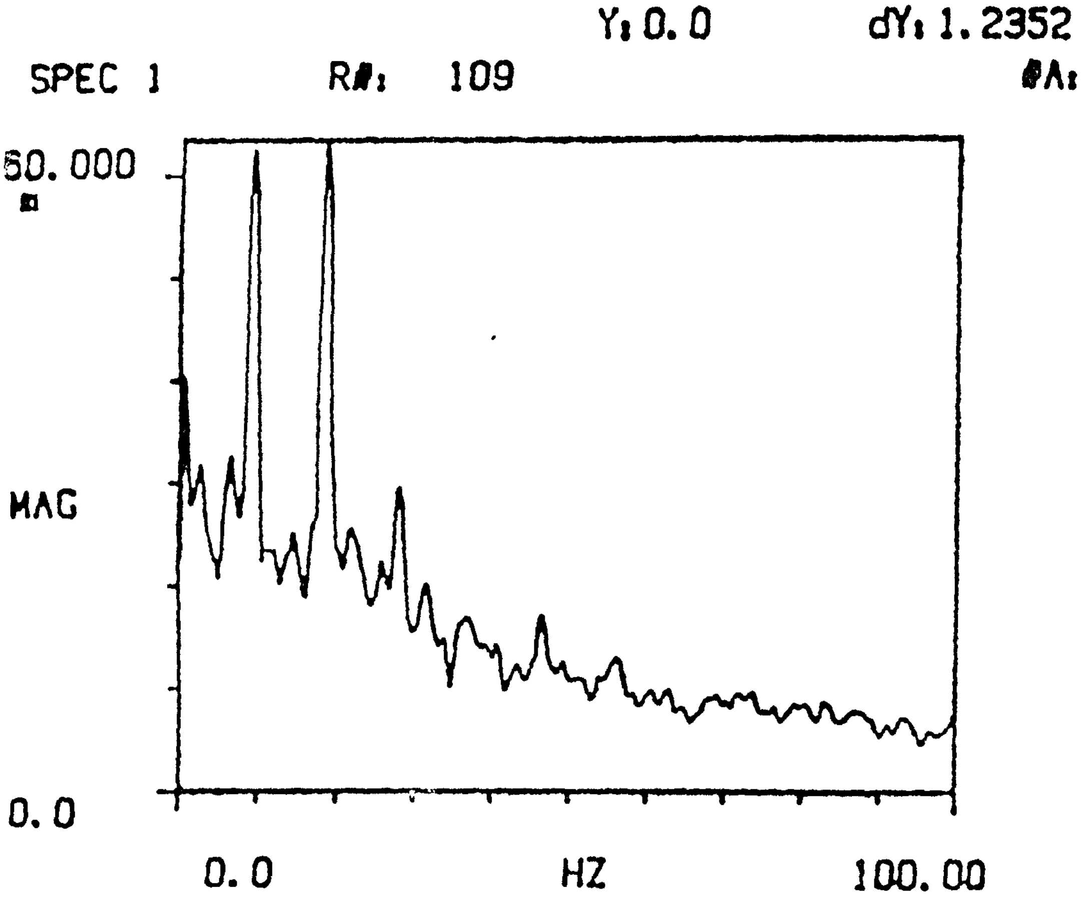
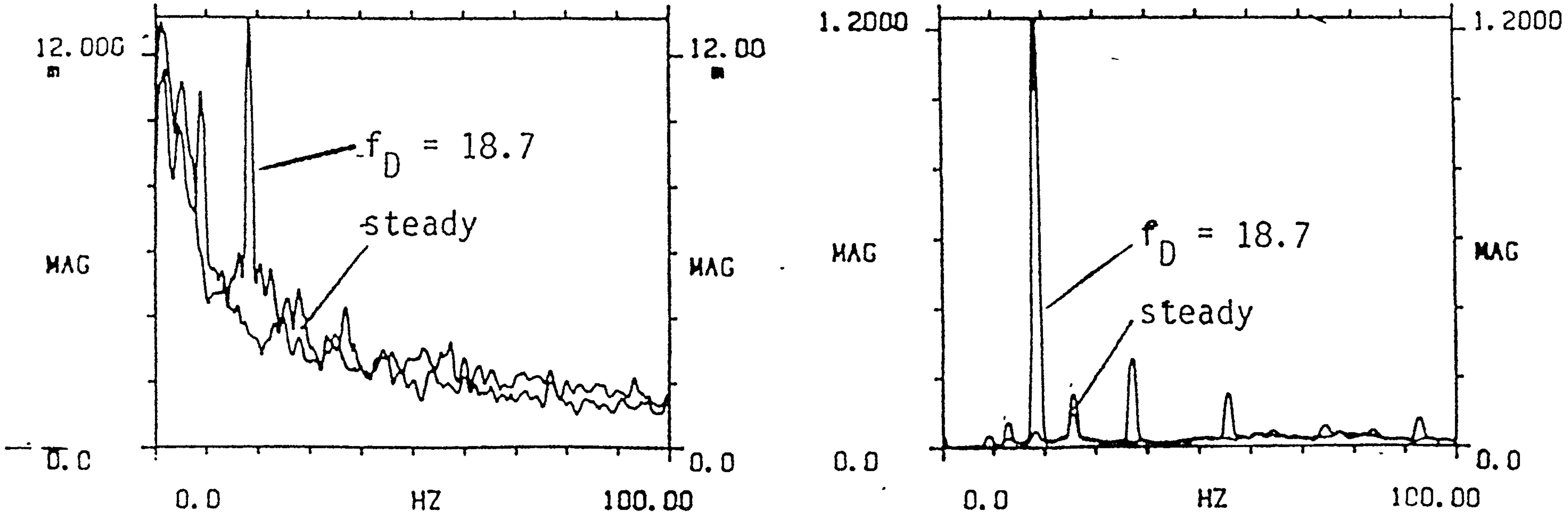


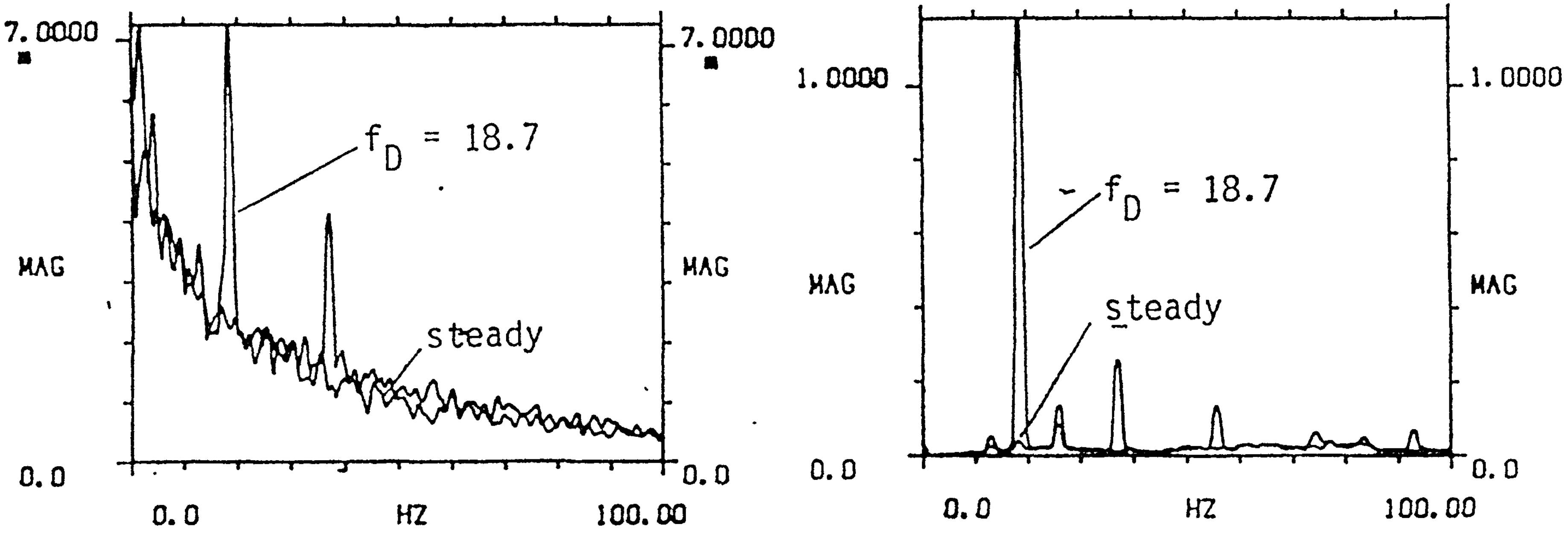
Fig. 4 Spectrum of the velocity measured in the wake of the triad for Re = 25,000, L/D = 1.1 and driving frequency f_D = 18.7 Hz.



(a)

(b)

Fig. 5 Spectra of (a) skin friction and (b) pressure at $\theta = 40°$, for Re = 25,000, L/D = 1.1 and f_D = 18.7 Hz.



(a)

(b)

Fig. 6 Spectra of (a) skin friction and (b) pressure at $\theta = 140°$, for Re = 25,000, L/D = 1.1 and f_D = 18.7 Hz.

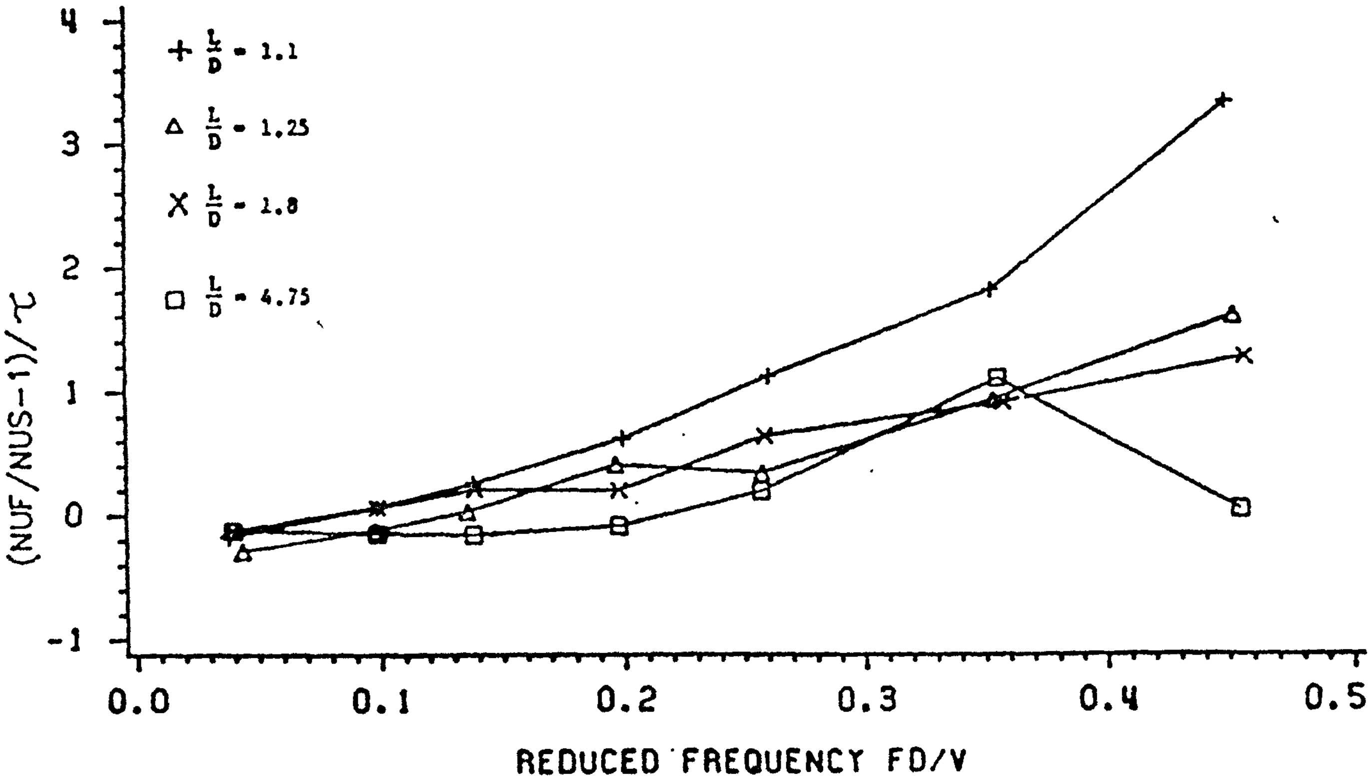


Fig. 7 Heat transfer increase per amplitude of flow pulsation.

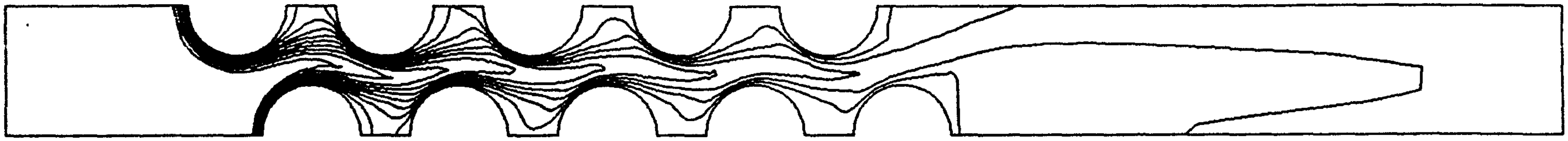


Figure 8a Isotherms for five-row-deep bundle of cylindersin figure 1a; Re = 200, P/D = 1.5 and PR = 0.7

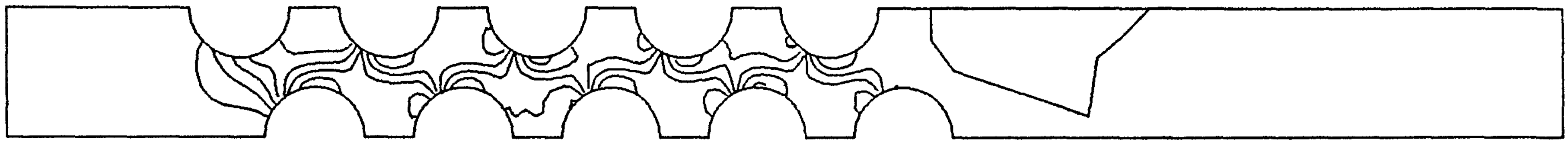


Figure 8b Isobars for five-row deep bundle of cylinders in figure 1a: Re = 200, P/D = 1.5

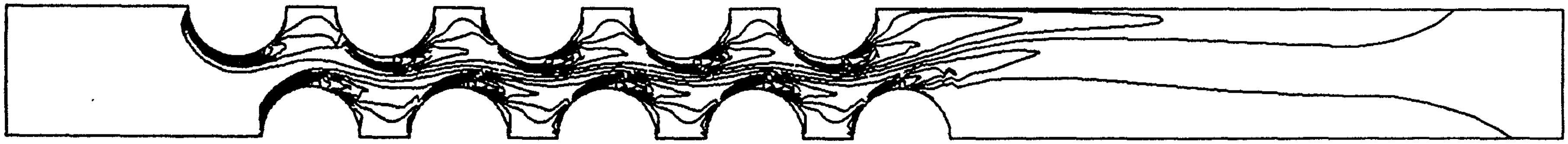


Figure 8c Isovorticity lines for five-row-deep bundle of cylinders in figure 1a; Re = 200, P/D = 1.5

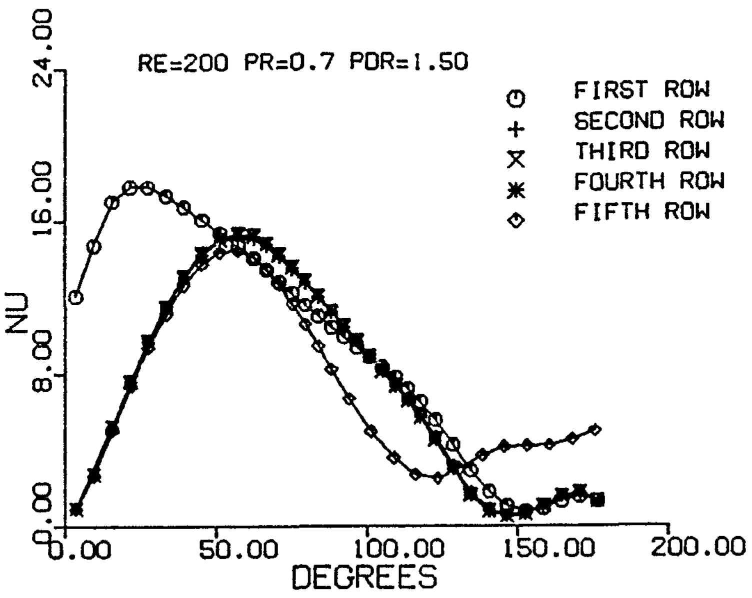
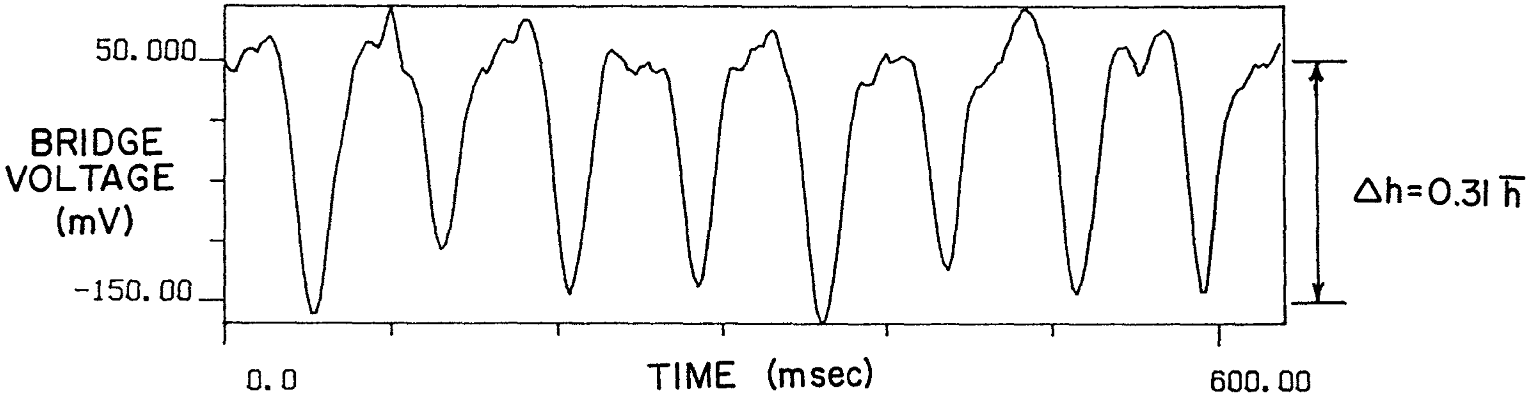
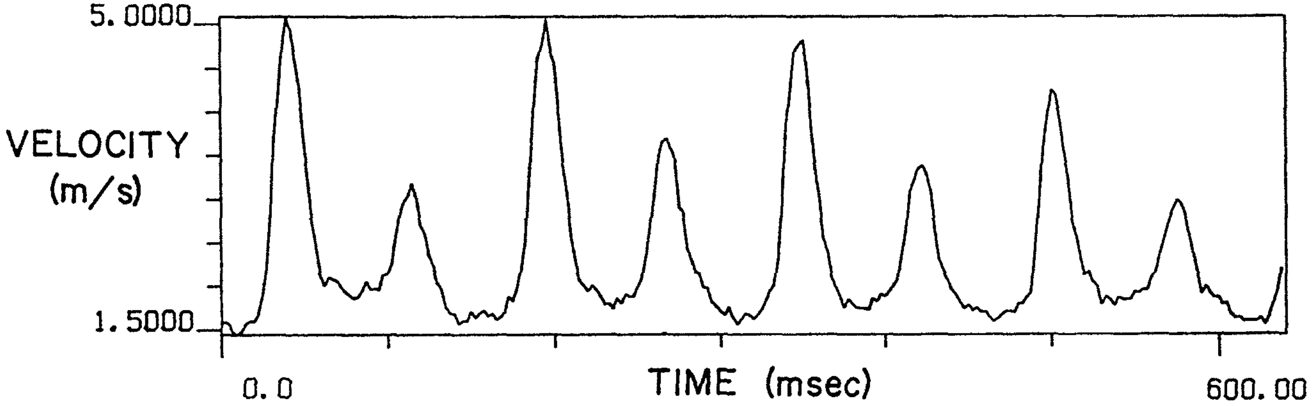


Figure 9 Distribution of local heat transfer coefficient around the bottom five cylinders numbered in figure 1a for Re = 200, P/D = 1.5



a) Heat Transfer



b) Velocity

Fig. 10 Sample Time Records of Velocity and Heat Transfer at $\theta = 120^{\circ}$

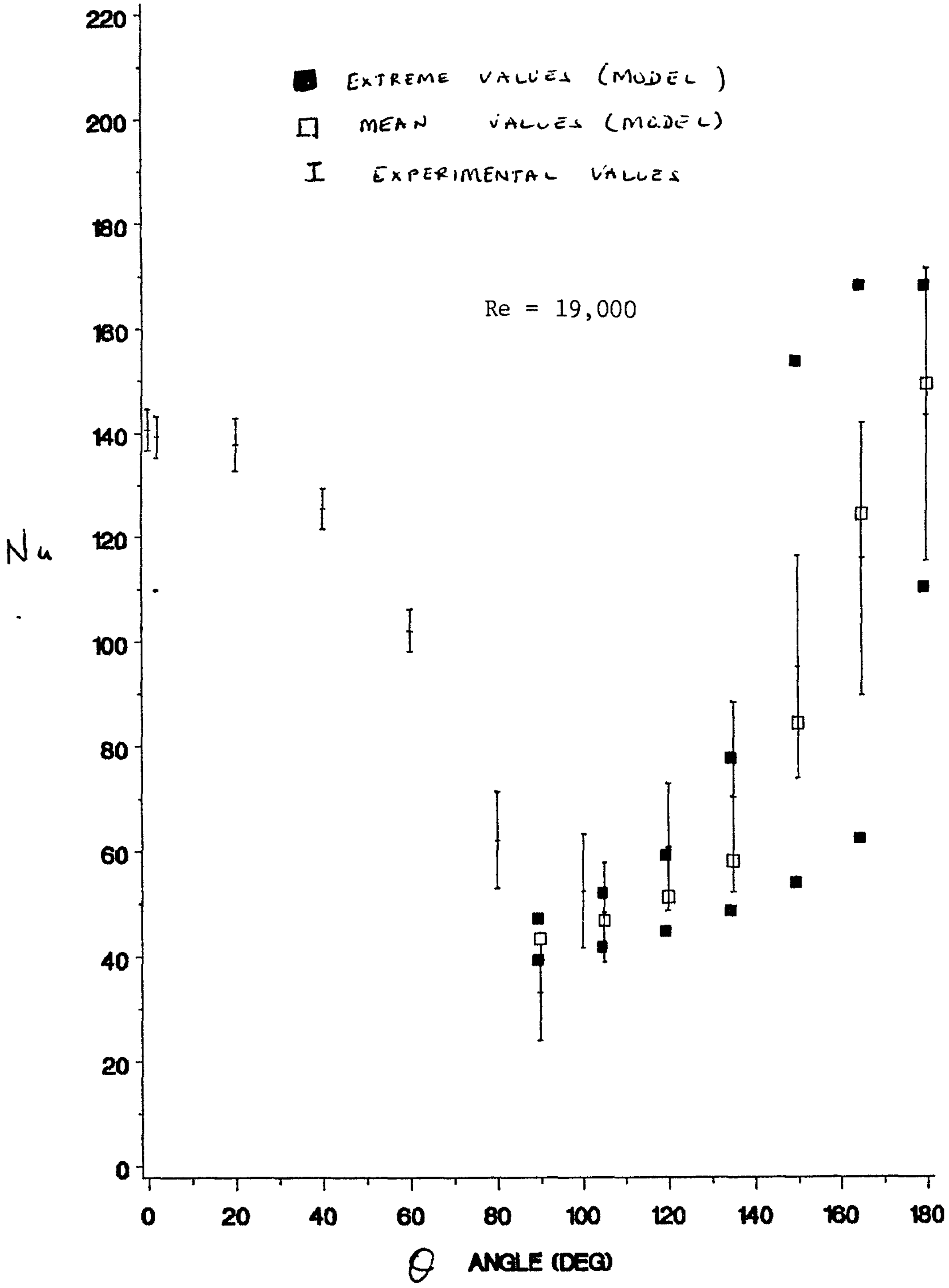


Fig. 11. Comparison of fluctuating amplitudes - experiment and model.