CHAPTER 5

IMAGING OF TRANSIENT FLUID FLOW AND THERMAL PHENOMENA IN COMMUNICATING CHANNELS

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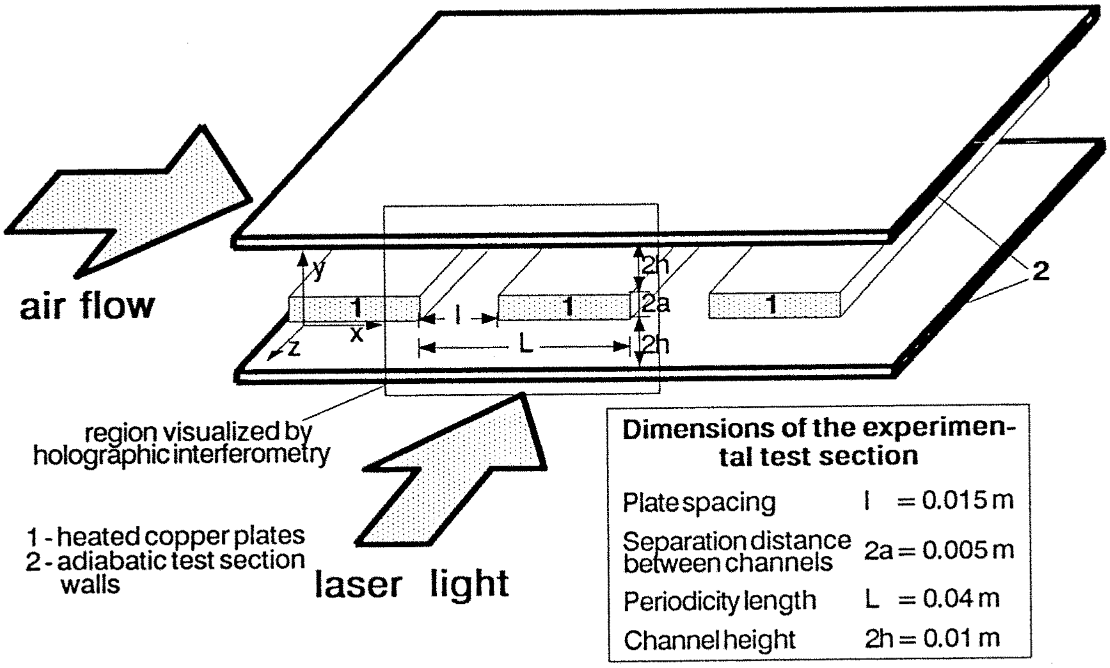
1. INTRODUCTION

Visualization is a powerful tool in the investigation of complex physical phenomena, due to the fact that the human visual perception system is well adapted to process complex visual information and extract visual information from images. Frequently, a graphical presentation of data is easier to understand and analyze than the corresponding sequences of numerical data, especially for data sets describing spatial structures of time varying phenomena. Visualized temperature, velocity and flow fields enable a better insight into the process under consideration and they can serve as complement in addition to the quantitative data. Visualization images are obtained using various experimental techniques, they can also be generated from data originating either from point measurements or from numerical simulation. On the other hand, quantitative data can be extracted from images obtained using different experimental visualization techniques. The different imaging techniques have experienced a dramatic development in the past decade, especially due to the rapid development of computer technology which enables fast manipulation of large quantities of data, the solution of complex mathematical models, and it is also a fundament for the implementation of digital image processing techniques in combination with the recording of images with modern video equipment.

A combined experimental and numerical visualization of the fast evolving thermo–fluid phenomena in oscillatory flows in compact heat exchangers is presented here. The investigated *communicating channels* geometry shown in Fig. 1, is a model for the rectangular plate–fin, offset–fin, offset strip–fin, and louvered–fin surfaces, frequently employed to improve the performance of *compact heat exchangers*. It consists of a succession of parallel plate segments aligned parallel to the flow. The working fluid is air and the direction of air flow is indicated in the figure. The top and the bottom flat walls are adiabatic, and the thermal boundary condition on the heated plates is characterized by uniform heat flux. The objective of this work is to analyze the oscillatory internal flow pattern and the corresponding temperature fields both experimentally and numerically.

Optical methods have proved to be especially convenient for the measurement of complex flows, as they provide measurement data without disturbing the investigated phenomenon. A variety of experimental visualization techniques have been developed to gain insight into a physical process



Dimensions of the experimental test section

Plate spacing	l	= 0.015 m
Separation distance between channels	2a	= 0.005 m
Periodicity length	L	= 0.04 m
Channel height	2h	= 0.01 m

Figure 1: Schematic of the investigated geometry and the physical situation.

[7, 10]. In the experimental visualization of temperature fields in the communicating channels geometry, the method of holographic interferometry was selected, and the fast evolving phenomenon was recorded using high speed cinematography.

The applications of field measurements which provide information on the whole fluid field at a certain time instant, in the quantitative analysis of physical processes were until recently very limited. This was due to the complexity of the extraction of quantitative data from the images, a tedious and time consuming procedure when performed manually. The availability of modern digital image processing equipment has enabled a relatively fast and easy analysis of visualization images. As result of the digital image processing procedure, the extracted data are visualized in a form which emphasizes the important features of the investigated phenomenon [5]; the flow structure may be shown in form of three dimensional images, the temperature fields obtained by evaluating the interferometric fringe pattern can be presented graphically as function of the spatial coordinates, and from the temperature distribution, heat transfer data can be evaluated [3]. Still, the applications of digital image processing in holographic interferometry reported in the literature are concerned with the analysis of individual images of steady phenomena or of the instantaneous state of an unsteady process, as described, for example, by Hunter and Collins [6] and Osten et al. [8].

In real situations and practical applications, processes are generally unsteady, and very often the complete information contained in the image is not necessary for a quantitative analysis of a temporal sequence; the development of events, the propagation of characteristic points in space is frequently of interest to the investigator. A complete analysis may be performed for a few selected images at characteristic time instants. In this work, a digital image processing technique is implemented in the analysis of transient temperature fields recorded as high speed image sequences.

The applications of *computer graphics* to flow visualization are relatively new and they involve the use of modern high–performance computer graphics techniques to depict and project the resulting data, although the computer system requirements for unsteady flow visualizations are quite substantial. These graphics techniques not only enable visual interpretation of the details of numerically generated flow fields but also allow to make comparisons between numerical solutions and visual representations of the actual flow obtained through experimental means. Numerical simulation complements the information obtained experimentally with insights into the instantaneous distributions of variables, such as velocity and pressure, which are very difficult to study in detail in experiments. Numerical animations were resorted to, based on an Eulerian framework, to analyze the problem from the computational viewpoint. Massive amount of data was generated and processed with the help of high–resolution graphics techniques. The numerical results are presented as computer–animated films as well as instantaneous plots.

2. METHOD OF STUDY

2.1 The Experimental Set–Up and the Experimental Procedure

The experimental arrangement: The experimental duct has a rectangular cross–section with parallel walls and dimensions as indicated in Fig. 1. The top and bottom walls are near adiabatic and ten copper plates in the mid–plane of the duct are heated with electric heater foils. The temperatures of the plane walls and heated plates are monitored by thermocouples to provide reference values for the interferometric measurements. The experimental visualization of the temperature fields is performed on the ninth plate, as the flow is periodically fully developed on this plate. The dimensions of the test section were selected to provide essentially two dimensional flow and temperature fields. Details about the experimental arrangement and about the measurement technique are discussed by Herman et al. [4] and Amon et al. [2].

The experimental method: The *real–time technique of holographic interferometry* has been selected for the experimental visualization of the fast evolving temperature fields, as it enables the visualization and quantitative measurements of temperatures with high spatial and temporal resolutions without disturbing the investigated phenomenon. Details on the method of holographic interferometry applied to heat transfer measurements are available in the literature [11]. The optical arrangement used in the measurements described in this paper has been discussed in detail by Herman et al. [4]. The temperature fields were recorded by *high speed cinematography* at rates up to 600 picture frames per second.

2.2 Mathematical Model and Numerical Solution Technique

Velocity and temperature fields were visualized using numerical techniques by considering Newtonian, incompressible two–dimensional flows with constant properties, which are governed by the unsteady Navier–Stokes and energy equations. Natural convection, viscous dissipation and variation of the thermal properties are neglected in the formulation of the problem. The velocity boundary conditions are Dirichlet on the rigid walls and periodic in the streamwise direction (Fig. 1). The thermal boundary conditions are uniform flux on the interrupted plates with adiabatic top and bottom walls. The numerical approach followed is that of direct numerical simulation of the unaveraged Navier–Stokes and energy equations by the *spectral element method* [9]. Details on the mathematical formulation and the numerical method of solution are presented by Amon et al. [2].

2.3 Extraction of Unsteady Data from Interferograms

Interferograms contain continuous two dimensional information on the field variable (in our investigations it is the density and the corresponding temperature field) coded as irradiance distribution in form of fringes representing isotherms. The existence of visual information is one of the important advantages of this measurement technique, but, having the amount of information contained in a single interferogram in mind, the extraction of quantitative data has always presented a serious problem and limited the applications of interferometry. Interferograms were usually evaluated by accurately measuring the location of fringe irradiance minima and maxima with a micrometer under a microscope combined with a photometer, and the data obtained in this way were evaluated with a computer. In transient real–time measurements several hundreds or thousands of images are recorded for a single state. The time history of an investigated feature is obtained by first identifying the feature in a sequence of interferograms and then analyzing its change by comparing the successive interferograms in the sequence. The problem shows some similarities with the measurement of flow velocities by particle imaging velocimetry: here the displacement of a particle between the two exposures is measured to determine the flow velocity, and the two images are recorded on the same picture frame. In the analysis of transient phenomena, the problem of simultaneous visualization and quantitative comparison of individual images is added to the original data reduction problem and this calls for new solutions in the evaluation process.

In our investigations, we have developed a *digital image processing* procedure, based on low-cost image processing hardware and commercially available software, to analyze the unsteady temperature fields. The configuration of the digital image processing system is presented in Fig. 2. In the high–speed measurements, interferograms were first recorded on 16 mm film and the images on the film were then analyzed using a video camera connected to a digitizer card in a personal computer. The images are sampled with a spatial resolution of $768 \cdot 512$ pixels. The information on the irradiance value is quantized as 256 grey levels. The image coded in this way can be observed on the high resolution screen in the different phases of digital processing.

A commercially available digital image processing software package (Bioscan Optimas Version 2.03) was used as basis for the development of the application specific software. It enables the recording of the images, setting marker flags to identify objects, it supports basic filtering operations to improve image quality and the generation of overlays. Data on pixel coordinates as well as the sampled and digitally coded irradiance values can be exported to external files for further evaluation. An Optimas specific programming language (similar in structure to the C language) allows for the development of application specific programs which can be combined with the basic program package. By using such software for the basic operations, the programming effort for the realization of the evaluation procedure was significantly reduced and more attention could be devoted to the specific problems.

The first step of the application specific algorithm is the determination of the position of the walls and the position of the heated plates. The evaluation steps are performed automatically and intervention of the operator is possible if correction or removal of the automatically generated markers is necessary. After defining a suitable coordinate system, the lines corresponding to irradiance minima and maxima are traced along each isotherm. In this way, data compaction was achieved by binarization; the grey level image was reduced to only two levels. The data compaction allows for easier analysis of the image by eliminating unnecessary details; it improves the

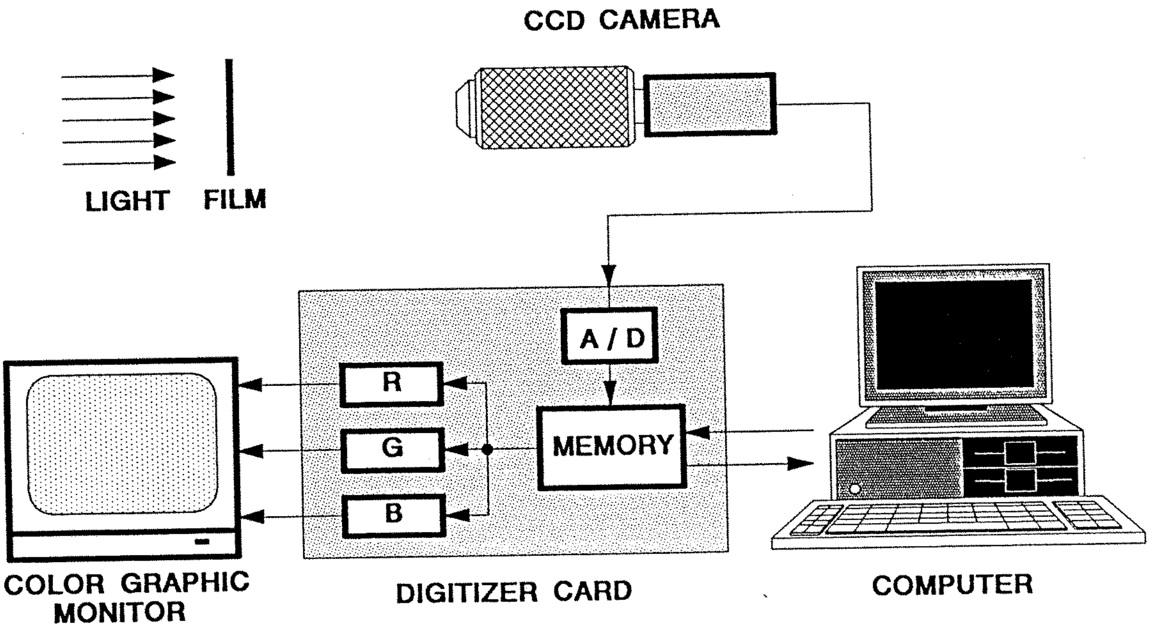


Figure 2: Schematic of the arrangement for evaluating high speed images.

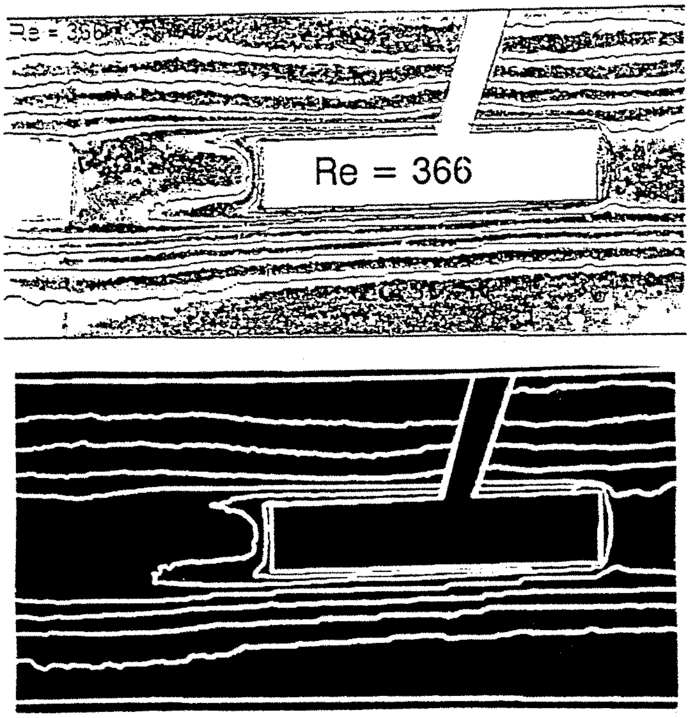


Figure 3: *Holographic interferogram recorded at Re = 366 with the superimposed overlay and the overlay indicating the positions of the walls and the locations of irradiance maxima along the interference fringes.*

processing speed and reduces memory requirements. The results of the tracing procedure are illustrated in Fig. 3. The sets of line coordinates obtained in this way are then stored separately in form of an overlay. The wall determination and the isotherm tracing procedure is repeated for the desired number of images and the corresponding data stored. In the following step, several overlays (usually not more than four to avoid loss of detail in the overcrowded picture) are superimposed, to observe the changes of the transient phenomenon in the investigated time interval on a single image. Color coding helps to distinguish between the different superimposed overlays. Particular events and features can be selected: marker flags can be set to identify the motion of a specific point between the individual exposures, as indicated in Fig. 4. Due to the complexity of the analyzed images, these markers are set manually, as the judgement of the operator in identifying the characteristic points of a set of images is essential. For the investigated physical situation, automatic data processing is not possible without the development of sophisticated image recognition algorithms. The coordinates of the marked events can be exported to external files and these data files are then subject of further evaluation.

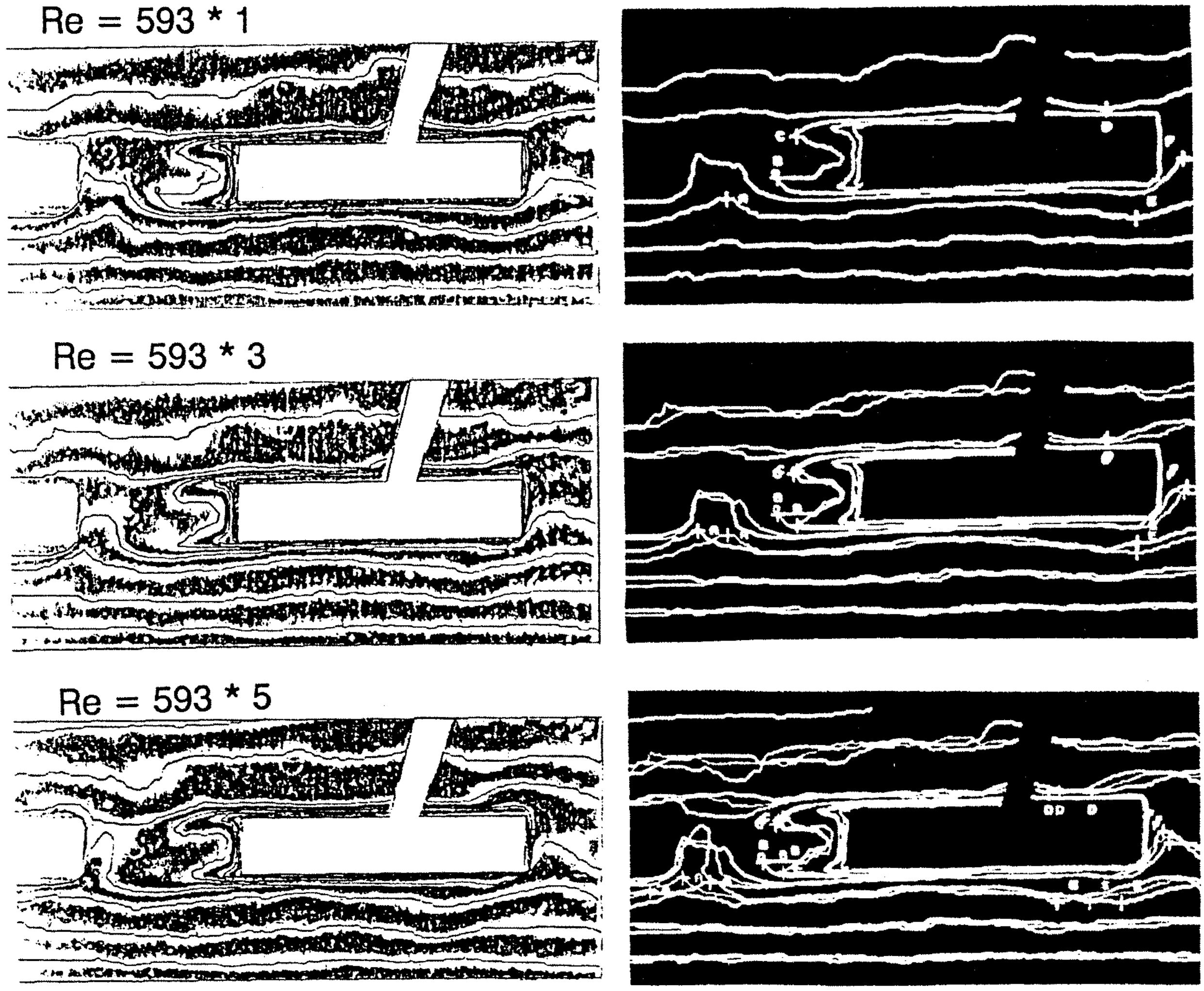


Figure 4: *Three holographic interferograms visualizing the transient temperature fields in the communicating channels at $Re = 593$ recorded at three time instants with the superimposed overlays and the superimposed overlays corresponding to the irradiance maxima obtained in the data compaction procedure.*

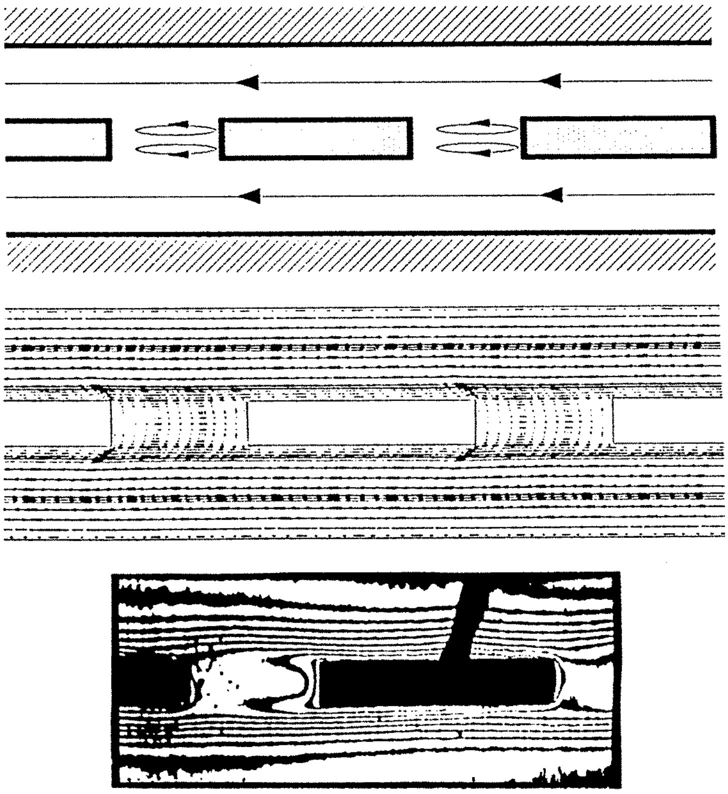


Figure 5: Schematic of the physical situation, velocity field obtained by numerical simulation and temperature field visualized by holographic interferometry for the steady flow situation (subcritical flow regime).

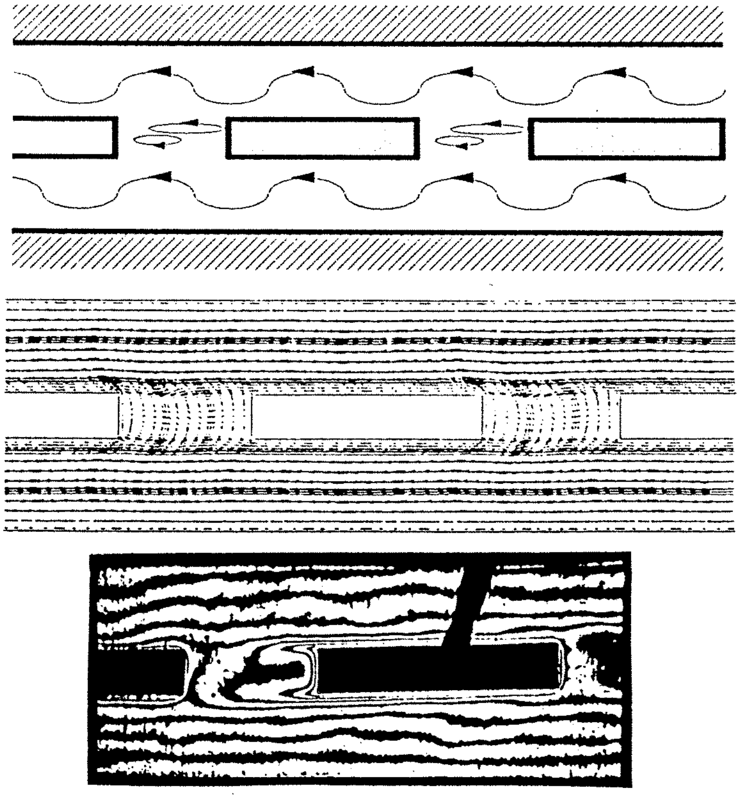


Figure 6: Schematic of the physical situation, instantaneous velocity field obtained by numerical simulation and instantaneous temperature field visualized by holographic interferometry for the unsteady flow situation characterized by simultaneous and symmetric vortex shedding in the region of the critical Reynolds number.

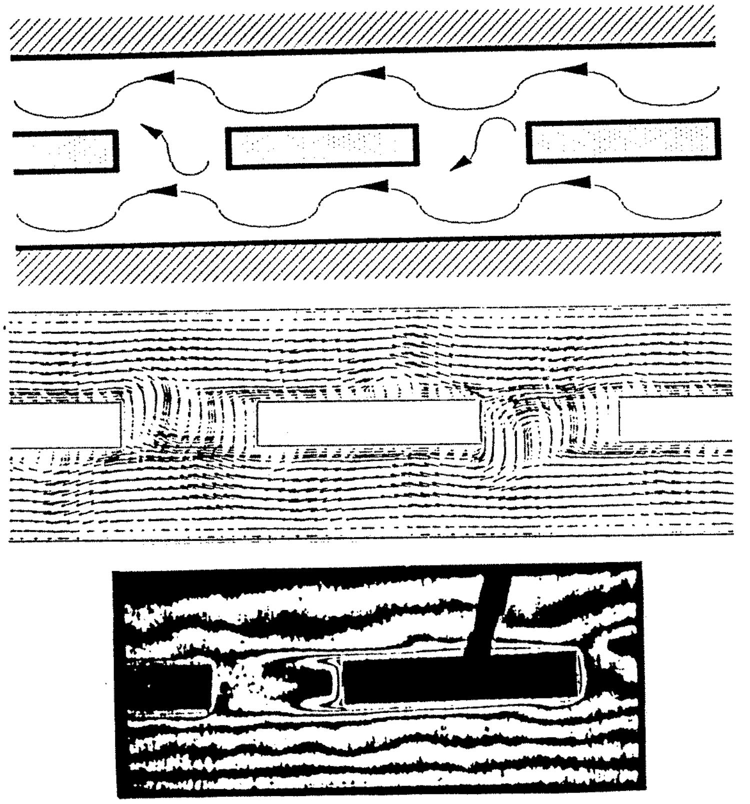


Figure 7: Schematic of the physical situation, instantaneous velocity field obtained by numerical simulation and instantaneous temperature field visualized by holographic interferometry for the time dependent flow situation characterized by antisymmetric vortical structures above the critical Reynolds number.

Wavelength and propagation velocity of the travelling waves and the frequency of the thermal oscillations in different regions of the communicating channels can thus asured. The procedure can easily be modified to evaluate different geometries and different physical situations.

3. IMAGING OF FLOW AND TEMPERATURE FIELDS

Figure 5 shows the schematic of the physical situation, the velocity fields obtained by numerical simulation and the temperature fields visualized by holographic interferometry for the steady flow situation. At flow velocities below the critical Reynolds number (the Reynolds number is defined as $Re = (3/2)v_m h/\upsilon$ with v_m as channel-averaged flow velocity, h as channel height and υ as the kinematic viscosity), two counter-rotating vortices are aligned and confined to the communicating regions due to the strong viscous effects present in the low Reynolds number flows [1]. In the top and bottom channel regions, the velocity distribution is nearly parabolic, the temperature fields are steady and the isotherms are parallel.

At Reynolds numbers above the critical value for the onset of oscillations, the vortices are unsettled and the steady state of the flow is disrupted. This physical situation is illustrated schematically in Fig. 6, together with the corresponding temperature and velocity fields. The critical Reynolds number, determined both experimentally and numerically, was found to be around $Re = 200$ for the investigated geometry. The vortices communicate with the main flow regions inducing a better mixing of the flow. The vortical structures in the two successive communicating regions are identical and they are rotating in the same direction. The flow structure in the communicating regions is in agreement with the structure of the travelling waves in the main channels: an even number of waves (four) spans the twice geometric periodicity length at any instant of time. This behavior is reflected in the structure of the temperature fields: waviness of the isotherms in the main channel regions (the waves are travelling in the flow direction) can clearly be observed as well as the oscillations in the communicating regions.

At still higher Reynolds numbers (Re ≥ 300), the velocity vector fields in the communicating regions are antisymmetric and the vortices are ejected in a staggered fashion to the upper and lower channels. An odd number of travelling waves (three) spans the twice geometric periodicity length at any given instant of time. The structure of the travelling waves is visualized in the temperature fields. Figure 7 illustrates this physical situation. At Re = 593 a bistable oscillatory regime has been detected. Small perturbations of the flow can cause the switching between the two regimes.

Figure 8 shows the flow pattern in terms of *instantaneous velocity vectors* at Re = 225 corresponding to the physical situation illustrated in Fig. 6. In Fig. 9, the instantaneous isotherm plots at Re = 250 are presented as a sequence of six time frames during one flow cycle. One flow cycle corresponds to the time in which the temperature at a fixed point undergoes a complete oscillation about the mean value. When compared to the history of the temperature fields recorded by holographic interferometry at Re = 366 and Re = 593 in Figs. 10 and 11 respectively, a good agreement can be found. These pictures demonstrate the complex separation phenomena, the multiple thermal boundary layer restarting and the effect of the separated flow on the resulting temperature distribution. The structure of the travelling waves as well as the propagation of the thermal wave can be followed in time through the evolution plots. The temperature fields show the waviness of the flow more clearly than the velocity vector plots. In this sense, the temporal sequence of isotherms is a thermal visualization of the *Tollmien–Schlichting waves* present in the main channel.

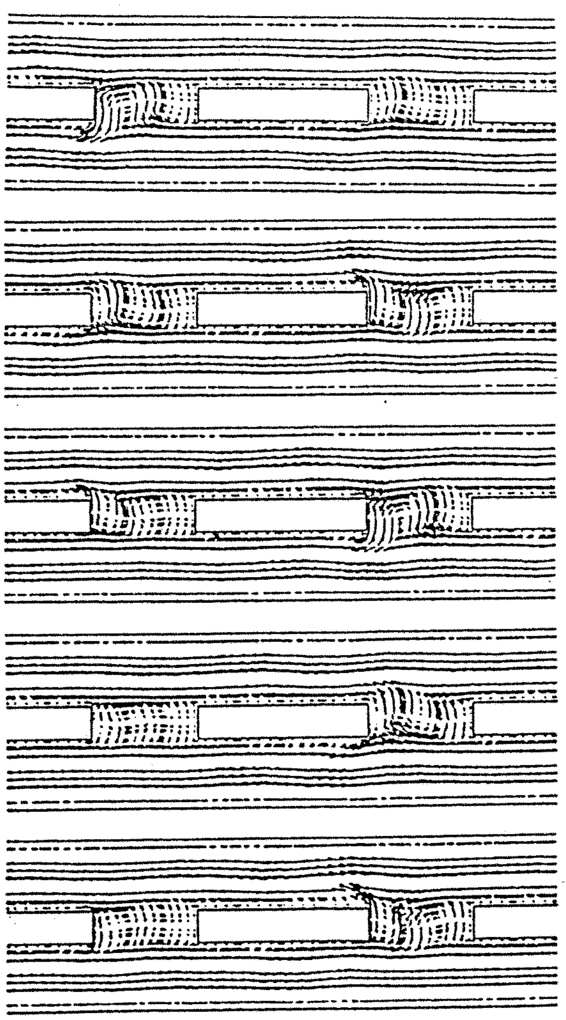


Figure 8: *Instantaneous velocity vectors at Reynolds number 225 at various times during the flow quasi-periodic cycle.*

From the experimentally visualized *temperature fields*, quantitative data on the oscillatory nature of the investigated process was obtained using the digital image processing techniques described earlier. By comparing experimentally visualized images and by measuring the locations of the characteristic points in the vortex region in a sequence of images, the oscillatory data was extracted. The distance between the isotherm extreme and the midpoint of the vertical trailing edge segment was measured in a sequence of 35 interferograms. Figure 12 shows the results of the *Fourier analysis* performed on the data on variation of the isotherm extreme in the vortex region behind

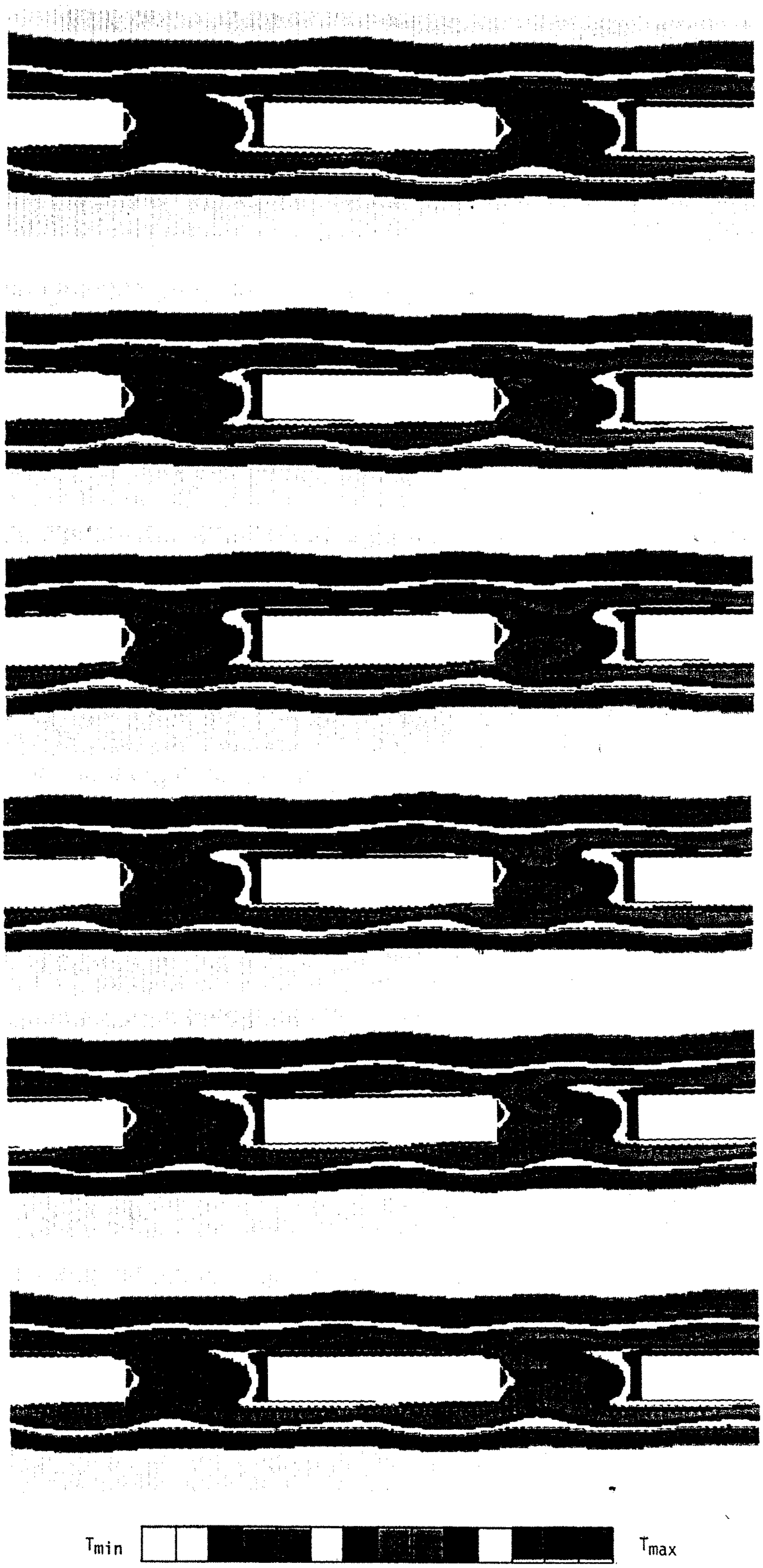


Figure 9: Instantaneous isotherm plots at Reynolds number of 250 for various times in a flow cycle.

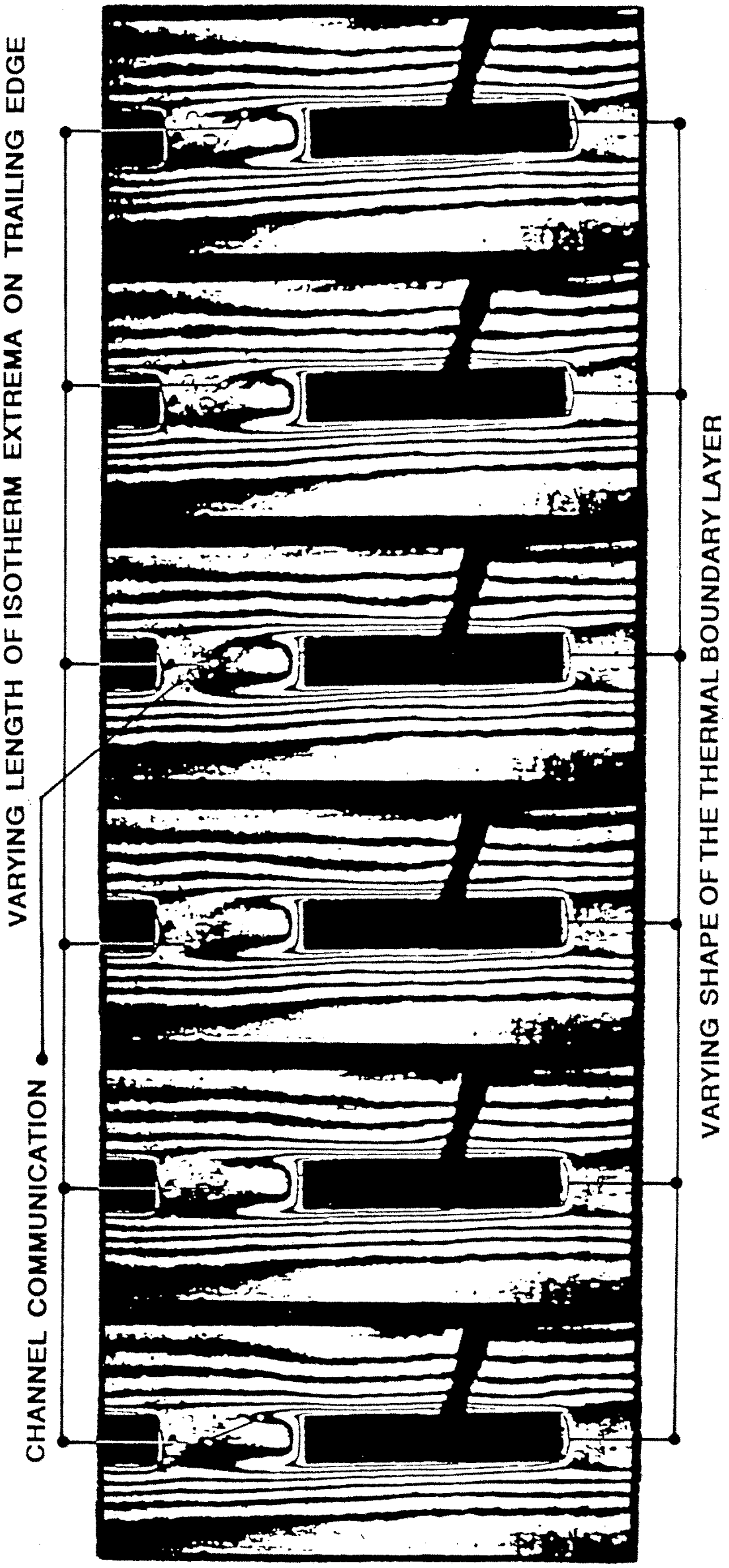


Figure 10: *Instantaneous temperature fields visualized by holographic interferometry at Re = 366 and recorded at the rate of 400 picture frames/s. The time interval between the exposures is 0.01 s.*

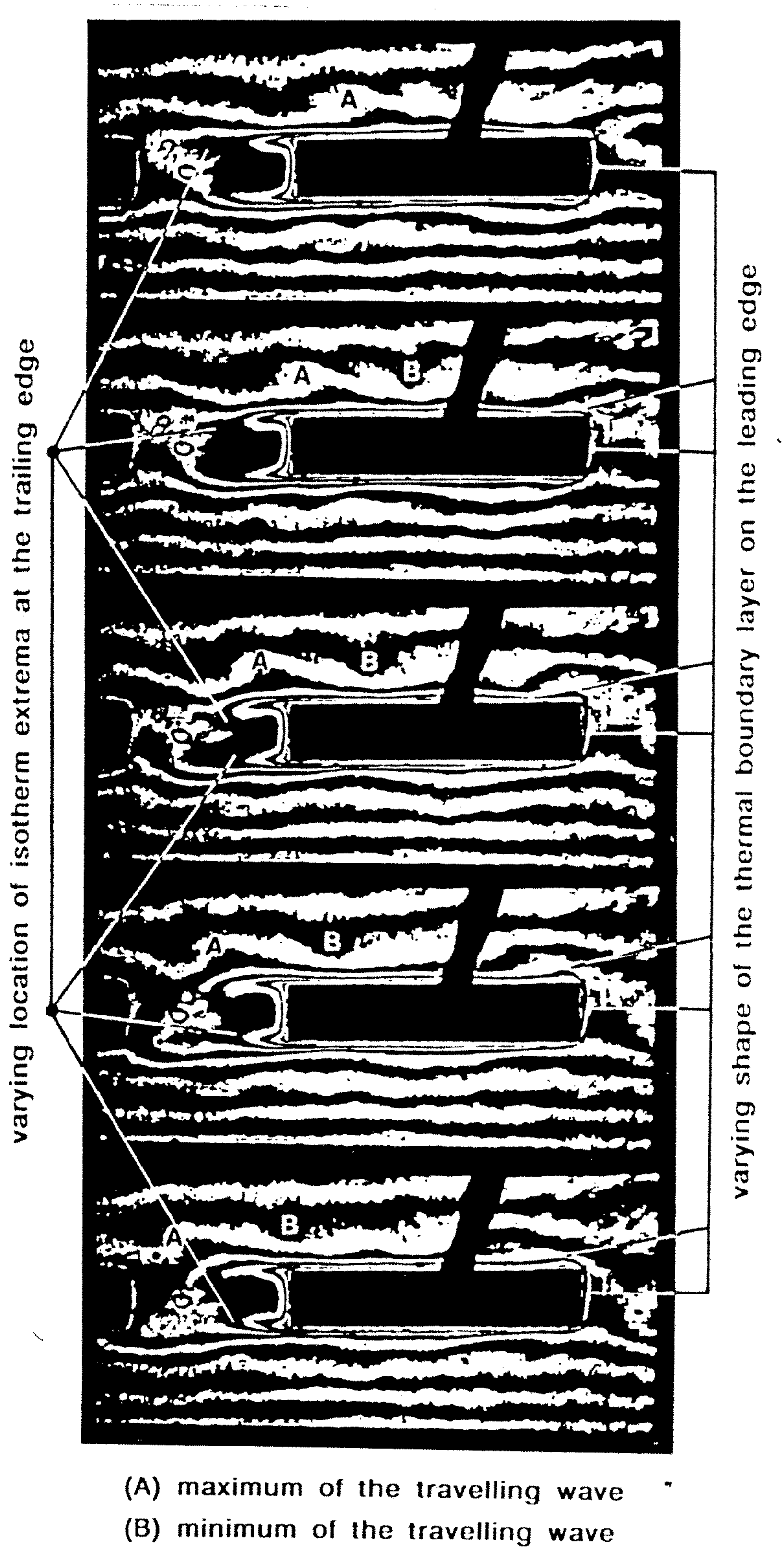


Figure 11: Instantaneous temperature fields visualized by holographic interferometry at Re = 593 and recorded at the rate of 600 picture frames/s. the time interval between the exposures is 0.005 s. (A) – maximum of the travelling wave; (B) minimum of the travelling wave.

heated plate at Re = 366. The first peak closely matches the Tollmien–Schlichting frequency obtained from the solution of the Orr–Sommerfeld equation and this is also in agreement with the results obtained by numerical simulation (24.97 Hz).

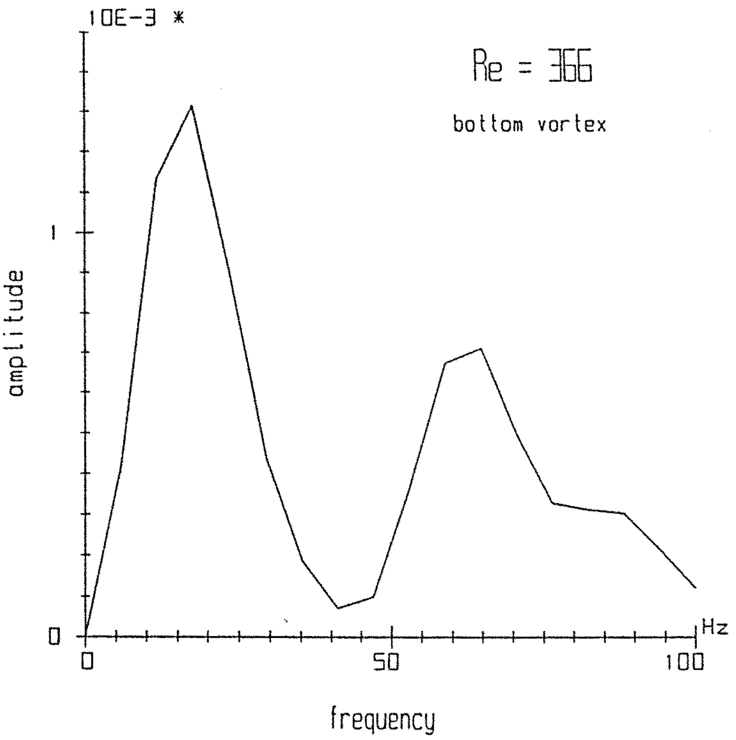


Figure 12: Amplitude spectrum of the oscillations in the vortex region at Re = 366.

An *animation graphics* technique has been used to facilitate the visualization of the time–varying temperature fields. All computed results are converted into a series of frame images using a package of subroutines called DrawCGM available at the Pittsburgh Supercomputing Center, which can directly create a CGM metafile. Essentially, the user has three sets of calls in the code. The first establishes the color table which provides the map between the data values and the colors ultimately seen on the screen. The next set of calls takes the temperature array, scales it to the appropriate size, converts the floating point data to integers in the range of 2 to 255 and draws the resulting integer array into the CGM file. At this point, facilities like color bars and labels are added. This set of calls is made each time a frame is dropped. Thirty frames are used to produce a computer–aided animation for one second. After the last image is created, the frame images are recorded on a video tape.

The highlight of this work is a videotape illustrating the evolution of the temperature fields obtained by experimental visualization using holographic interferometry as well as by numerical animation for two complete cycles. The different steps of the digital image processing procedure in the extraction of quantitative data from interferograms were also recorded on video.

4. CONCLUSION

A combined experimental and numerical investigation of oscillatory thermo–fluid phenomena in communicating channels was performed using holographic interferometry, numerical simulation and computer aided animation. The results of the numerical animation show good agreement with the experimentally visualized temperature fields. By using a modern digital image processing technique, the extraction of quantitative data on the unsteady temperature fields from the interferograms and the comparison of images recorded at different time instants is possible. Thus, the necessary data for comparisons of the experimental and numerical results on the quantitative level is provided.

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