INFRARED THERMOGRAPHY AS A FLOW AND LOCAL HEAT TRANSFER VISUALIZATION TOOL

Saad Al-Kahtani, Eball Ahmad and Yousuf Al-Yahya

King Abdulaziz City for Science and Technology (KACST), P. Box 6086, Riyadh-11442, Saudi Arabia.

E-mail: skahtani@kacst.edu.sa

ABSTRACT

The scope of the measurement & calibration laboratory at the Measurement and Instrumentation Center (MIC) of King Abdulaziz City for Science and Technology (KACST) is being extended to include the development of several new unique experimental facilities to facilitate research in relevant areas of measurement & calibration. One of these facilities, the Heat transfer Jet Impingement Facility (HJIF), which is being developed to facilitate transient conductive heat transfer research studies associated with parallel and imposed axial flow on surfaces of various complexities especially in applications where accurate local heat transfer information is required. A special feature of the HJIF is that, its infrared thermography systems provided direct visualization of flow and heat transfer pattern from the investigated surfaces. The technique and test facility are described and examples of infrared images for flow visualization of jet impingements and of obstacle elements placed in boundary layer are provided.

Keywords: *Jet Impingement, Axial Flow, Transient Heat Transfer, , Infrared Thermography, Flow Visualization.*

:الملخص

يسعى مركز الأجهزة العلمية بمدينة الملك عبد العزيز للعلوم والتقنية لتطوير قدراته البحثية من خلال بناء أوضاع تجريبية ذات علاقة بمجال القياس والمعايرة. أحد هذه الأوضاع التجريبية خاص بالهواء المدفوع والذي من خلاله يمكن دراسة الانتقال الحراري الفجائي لأسطح مختلفة سواء كان السريان عموديا أو موازيا للسطح وخاصة في التطبيقات الحرارية المعقدة. ويتميز هذا الوضع التجريبي باستخدامه للتصوير الحراري كنظام لاكتساب المعلومات الذي يُمكّن من إيضاح الظواهر الخاصة بسريان السوائل والانتقال الحراري. في هذا البحث سوف يتم وصف الطريقة المستخدمة في التصوير الحراري في الدراسات الحرارية الفجائية, كما سوف يكون هناك وصفا مفصلا لهذا الوضع التجريبي مع إبراز بعض الصور الحرارية التي توضح سريان الهواء بواسطة التاريخ الحراري المصاحب.

1. INTRODUCTION

Since its establishment in 1996, the Measurement & Instrumentation Center (MIC) of King Abdulaziz City for Science and Technology (KACST) has built good capabilities in the various aspects of technical support offered to the seven research institutes of KACST. Attention is now diverted to expand on the available services to include research and development by building and facilitating the use of unique experimental research facilities, which utilize some of the available resources at MIC. At present, two unique experimental setups are being developed at MIC calibration laboratories. One of these is the Heat transfer Jet Impingement Facility (HJIF), which is designed and constructed at MIC laboratories utilizing the existing bench top wind tunnel as a flow intake system and the available infrared imaging equipment as a data acquisition system. Such facility should make the use of the relatively newly developed non-contact transient measurement techniques possible in flow and convective heat transfer studies at KACST.

It is well known that in the last 10 years, the application of the transient liquid crystals and infrared measurement techniques to surface flow and heat transfer studies have proved to be very effective in mapping the flow field and heat transfer process over surfaces with complex geometries [Sargent et al, 1998, Jackson et al, 1995 & Page, 1994]. Among those is heat transfer enhancement in modern application, such as heat exchanges, electronic devices, propulsion, and power system, etc. which requires a basic understanding of convective transport around three-dimensional elements and of jet impingement. Until recently, information concerning three dimensional roughness heat transfer has relied primarily on area-averaged measurement, which typically involve arrays of roughness elements [Chyu and Natarajan, 1996]. With this in mind the present study is an application of the non-contact infrared measurement technique to visualize flow and heat transfer pattern around three-dimensional elements and that of jet impingement. In 1996, Chyu and Natarajan performed heat transfer-mass transfer analogy using naphthalene sublimation technique to investigate heat transfer of several three-dimensional elements with good success [Chyu and Natarajan, 1996]. In this paper the test facility and the infrared transient technique are described and examples of infrared images for flow and heat transfer pattern of jet impingement and of three dimensional cubical, and cylindrical elements, which are obtained during early phase of the commissioning tests of the experimental facility are presented.

2. THEORETICAL BASIS OF THE TRANSIENT INFRARED TECHNIQUE

The transient infrared technique is similar to the thermochromic liquid crystal technique, which is fully explained in [Al-Kahtani, 1995]. It involves a flow of hot air, which is suddenly directed against a test surface initially at a uniform temperature. The surface temperature of the test piece is monitored by observing color changes resulting from infrared images and from this temperature history, the heat transfer coefficient distribution is obtained. Because the test surface is made of perspex, which has a low thermal diffusivity and conductivity, the heat conduction process into a test piece of sufficient thickness can be assumed to be that of one dimensional conduction into a semi-infinite medium. The surface temperature is then related to the surface heat transfer rate by the one-dimensional heat diffusion equation.

Top

3. EXPERIMENTAL FACILITY

The schematic diagram of the experimental rig which has been designed constructed and commissioned for the use in the present and future studies of flow and heat transfer is depicted in figure 1. It shows the essential components of the Heat transfer Jet Impingement facility (HJIF), namely; The Test Section, The Ducted Flow System, and The Data Acquisition System. A description of these components is presented below:

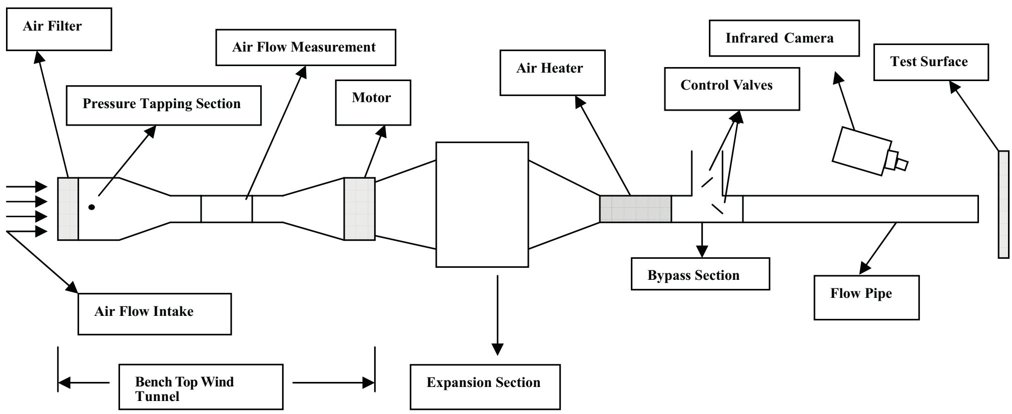


Figure 1: Heat Transfer Air Jet Impingement Experimental Facility.

3.1. The Test Section.

The test piece is mainly a square plate of a smooth surface made of perspex of 10 mm thickness. This thickness is sufficient enough to satisfy the semi-infinite assumption mentioned earlier. The test surface is painted black to increase its emissivity and decrease its reflectivity.

3.2. The Ducted Flow System.

As can be seen from figure 1 the ducted flow system forms the main part of the rig. Air is drawn in it, heated, and then directed towards the test surface through a ducted flow piping system. The main flow pipe diameter is 140mm, however, several sizes of the pipe section before the test surface ranging from 25mm to 140mm were made available to facilitate wide range of flow and heat transfer studies. The first section of the ducted flow system, namely, the flow intake system is a bench top wind tunnel, which has been described in ref [Al-Kahtani and Abdulkayyom, 1999] and reproduced here for clarity. The bench top wind tunnel measurement and calibration system is as depicted in figure 2. It is manufactured by OMEGA and it is mainly constructed from fiberglass and is designed to give highly uniform airflow over the whole length of the test section [Omega, 1995]. The air intake side is a honey comb baffle which is designed so that a constant and evenly distributed air intake is ensured. The test section has a cross section of 101.6 mm x 101.6 mm with a length of 152.5 mm and is constructed from clear plastic for easy viewing. A 60-mm extension of the test section is utilized for the insertion of the restrictive plates or for testing of air velocity meters (e.g. vane anemometers), when no restrictive plates in position.

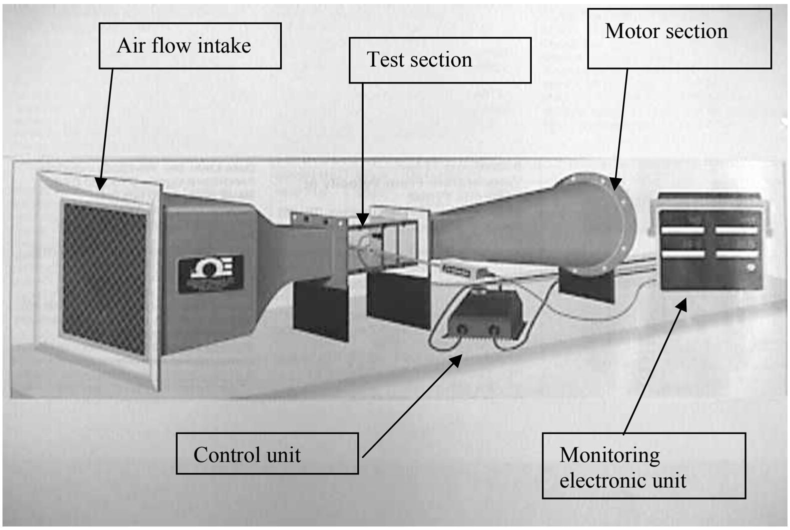


Figure 2. Wind tunnel test and calibration facility

The steady flow rate is determined by monitoring a highly repeatable differential pressure, which has been calibrated to the same wind tunnel as a system [Omega, 1995]. The wind tunnel is supplied with two restrictive plates for achieving low flow rates. Three air velocity ranges, which could be obtained through the test section of the wind tunnel are as listed in table 1.

Table 1. Available air velocity ranges

Wind tunnel configuration	Velocity ranges (m/s)
No restrictive plates	7.5 to 45 m/s
Restrictive plate A	1.25 to 6.5 m/s
Restrictive plate B	0.15 to 1.25 m/s

Top

A 12.5 mm threaded hole is provided at the center of the test section to facilitate easy insertion of various measuring probes in to the uniform flow. The air is drawn into the test facility by a variable speed (up to 10,000 RPM) 12 Amp AC motor which is located at the rear of the wind tunnel and it is manually controlled by a fine control unit. The wind tunnel is instrumented through an electronic unit, which has the facility to monitor differential pressure, atmospheric pressure, room temperature and humidity. The wind tunnel system (including the electronic unit) is supplied with a calibration certificate and data sheet traceable to National Institute of Standards and Technology (NIST).

The flow leaves the Wind Tunnel into an expansion section situated before the air heater. The air heater itself is electrically powered with a maximum power output of 8kW. It consisted of 2 heater elements, which could be operated independently or together.

After the air heater the bypass section, which contain two butterfly valves so that all the hot air flow was either exhausted to the atmosphere along the bypass line or directed into the test section. In order to avoid heat loss from the air to the ducting after switching the flow direction to initiate a test it was necessary to trace heat the ducting so it was preheated to a temperature equal to that of the hot air leaving the air heater. This was done by electrical heating of the bypass and the following pipe section by garden wire heaters which were carefully wrapped around the straight and curved sections respectively. The garden wire heaters were independently powered by two variable voltage power supply systems (0-30V) to provide, as nearly as possible, a uniform ducting temperature equal to that of the hot air. The air heater and the following sections of the axial flow system were lagged with a 50 mm, layer of fiberglass material to reduce the heat losses to the atmosphere. Thus after switching the flow, a uniform temperature profile can be obtained, In addition, the pipe at exit was capped during the initial heating process to avoid any heat leakage into the vicinity of the test surface which had to be initially at ambient temperature.

In order to monitor the pipe wall temperature during an experiment, several K-type thermocouples were spaced at approximately 300 mm intervals. They were resistance-welded onto the external surface of the ducting. The temperature signals were read from digital thermometers with switches. Other than these, there were three more thermocouples. One was in the center of the bypass, to monitor the gas temperature during the air heating process, the second was at the center of the pipe exit, to monitor the gas during a test, and the third was near the test section to record the ambient (test surface) temperature before a test.

3.3. The Infrared Thermographic System.

The available thermovision at MIC Laboratory (AGEMA 900) is utilized as a data acquisition system in this experimental facility. The system consists of two main units, namely; The Infrared Scanner (Camera) and The System Controller. The controller is a dedicated microcomputer designed specifically for the thermovision 900 system. The scanner is a compact and light weight instrument which allows ease of use. The main function of the scanner is to convert infrared radiations into digital signals that can be processed by the system controller to display infrared images of the object. The thermovision 900 scanner is designed to operate in the 2 - 5.4 μm band of the infrared spectrum with a scan rate of 20 Hz and an image resolution of 140 elements per line. This is interpreted in the processor to provide an image of 200 pixels per 130 lines. The infrared camera is calibrated at two working positions with respect to the flow direction, i.e., one position is in the direction of the flow at a view angle of about 20^0. The other position is perpendicular to the flow direction. Both positions are at a distance of 1 meter from the test section (surface).

4. QUALITATIVE RESULTS AND DISCUSSIONS

In this work a heat transfer air jet impingement facility was designed and built to facilitate forced convective transient heat transfer studies at KACST. Preliminary commissioning tests involving infrared visualization of flow and heat transfer pattern were carried out for two different flow arrangements, namely; Air jet impingement and a flow over a flat surface with two (three dimensional) obstacle elements. Two cases for each flow arrangement were chosen to carry out this first phase of the commissioning tests of this new and unique research facility. It must be mentioned here that the infrared data acquisition system provided detailed images in a high frequency rate which was recorded in video recorder and only few images will be presented in the following:

4.1. Air Jet Impingement.

A single and double inline nozzles were fabricated and used in these early phase flow visualization tests. Figure 3 shows the flow and heat transfer patterns for a single inline nozzle at the beginning, middle and end of test. The color-temperature scale of these images reflects the temperature distribution throughout the test surface i.e., the surface temperature of the test piece is monitored by observing the color change of the infrared images and from this temperature history, various information (e.g. local heat transfer coeffecients) could be deduced. Figure 4 shows the results for double inline nozzles. It can be seen that the stagnation regions for both single and double inline nozzles are the regions where the highest heat transfer occurs. The flow overlapping of the double nozzle is evident throughout the test which increase the heat transfer greatly in comparison to the single nozzle, which was equivalent in size to the double nozzles. It is clear from the above images (not completely symmetrical images) that in-house nozzle fabrication need to be improved to give better round images for better results.

4.2. Flow Around Cubical and Cylindrical Elements.

The flow and heat transfer processes are illustrated through the infrared images as can be seen in figure 5 for a cubical element in a boundary layer flow. The well known horse shoe vortex is developing in the stagnation region in front of the cube where the highest heat transfer occurs. This region is influenced by the flow process down-stream behind the obstacle element, i.e. the influence of the secondary vortices. Such influence can be seen from the three images, where it is clear that the horse shoe vortex is the largest in figure 5B. Whilst in figure 5C it can be seen that color pattern changes from brown back to green (i.e. from hot to cold) behind the cubical element. These flow processes which occur down-stream affect not only the flow and heat transfer processes behind the cube, but also results in a smaller stagnation region in front of the cubical element. Figure 6 is the visualization of the flow and heat transfer pattern around a cylindrical elements. Similar to cubical element , the well known horse shoe vortex for the cylindrical element is the largest in figure 6B, but, then it becomes smaller as can be seen in figure 6C. These and other surface heat transfer enhancing elements will be the subject of future detailed qualitative and quantitative studies.

5. CONCLUSION

A unique Heat transfer Jet Impingement Facility (HJIF) has been designed, constructed and commissioned to facilitate flow and transient convective heat transfer studies at KACST. Infrared visualization commissioning tests were performed which provided good images of the flow and heat transfer pattern for inline nozzles and boundary layer flow with three-dimensional obstacle elements. The heat transfer, as expected, was enhanced by these flow arrangements. The infrared flow and heat transfer visualization technique as applied in this work, did not only provide good qualitative assessments of some important flow and thermal transport problems, but also may prove to be one of the best techniques in transient convective heat transfer studies, especially when complex goemetries are involved.

REFERENCES

1. Al-Kahtani, S. A., 1995, "Studies of Heat and Mass Transfer from a Rotating Disk with and without an Imposed Axial Flow", Ph.D. thesis, University of Manchester.
2. Al-Kahtani, S. A. and Abdul Khayyoom, S., 1999, "Calibration Studies on a Bench Top Wind Tunnel Facility", 5^{th} Saudi Engineering Conference, Umm Al-Qura University, Mekkah, 1- 4 Mar.
3. Chyu, M. K. and Natarajan, V., 1996, "Heat Transfer on the Base Surface of Three Dimensional Protruding Elements", Int. J. Heat Mass Transfer Vol. 39, No. 14.
4. Jackson, J. D., Al-Kahtani, S. A. and He, S., 1995, "Investigation of Heat Transfer from an Imposed Axial Flow of Air to A Rotating Disk", EUROTHERM 46:, Heat Transfer on Single Phase Flow, Pisa, Italy, 3 - 4 July.
5. Omega Engineering Inc., 1995, Flow and Level Measurement Handbook and Encyclopedia, Vol. 29.
6. Page, R. H., 1994, "Infrared Thermography as a Flow Visualization tool", FLUCOME, Toulouse, France.
7. Sargent, S. R., Hedlund, C. R. and Ligrani, P. M., 1998, "An Infrared Thermography System for Convective Heat Transfer Measurements in Complex Flows", Meas. Sci. Technol. 9, No. 12.

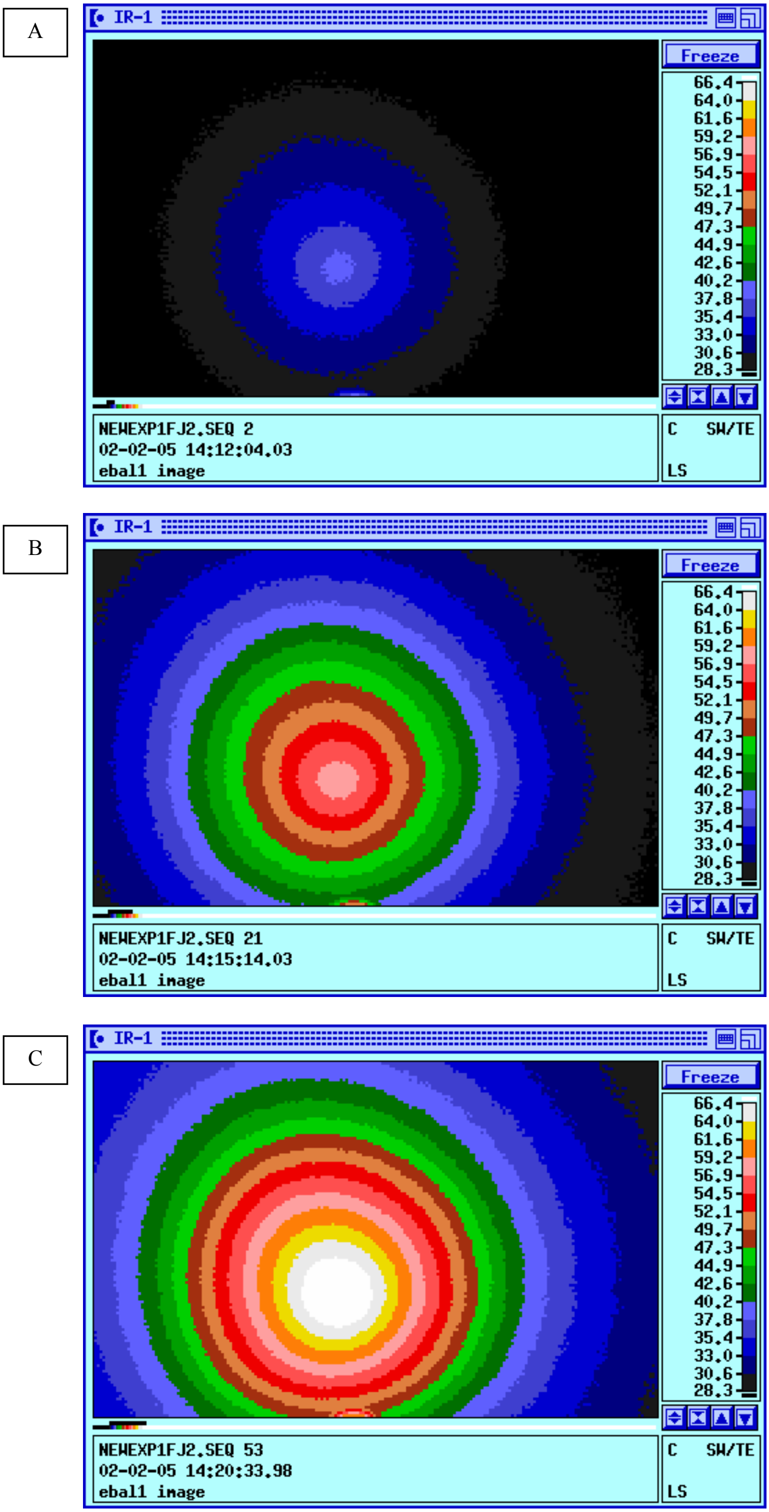
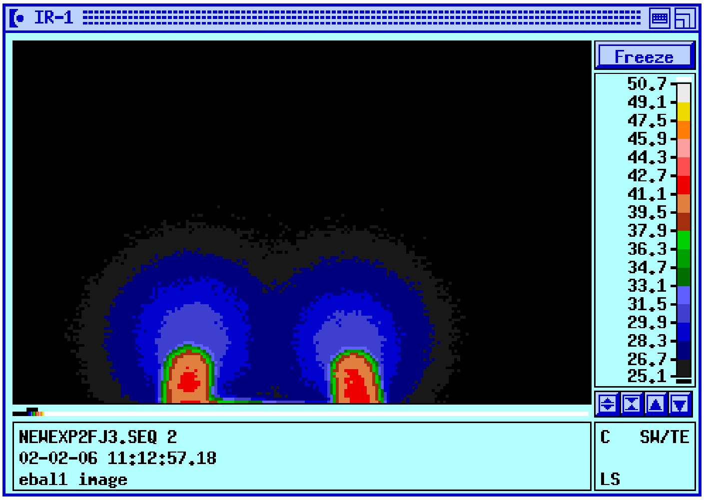
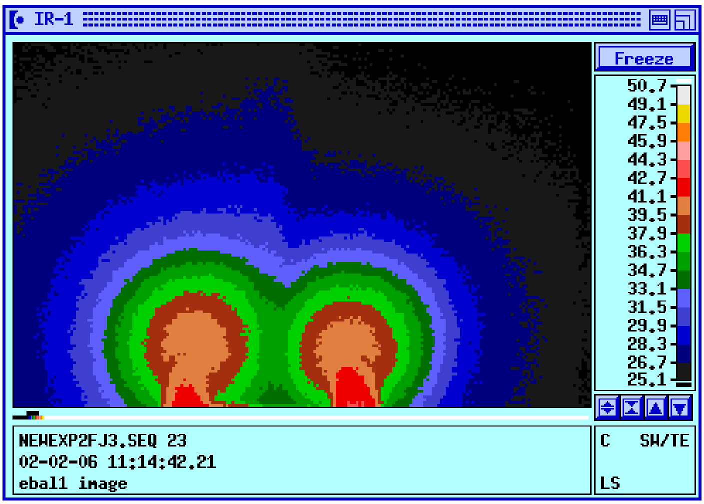


Figure 3: Flow and heat transfer visualization for single inline nozzle.

A



B



C

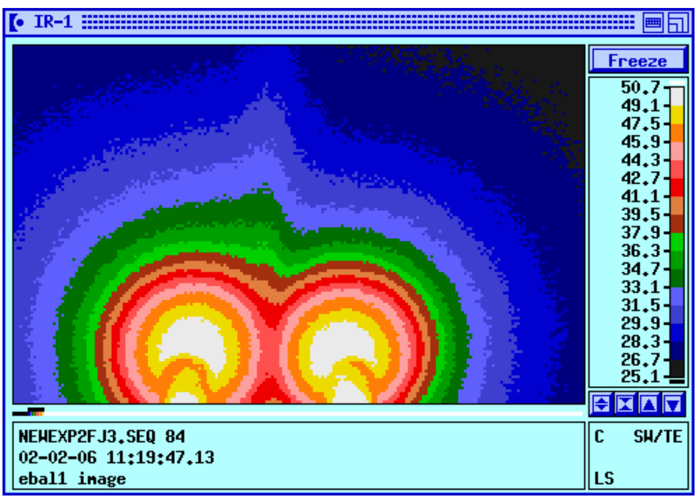


Figure 4: Flow and heat transfer visualization for Double inline nozzle.

Top

A

B

C

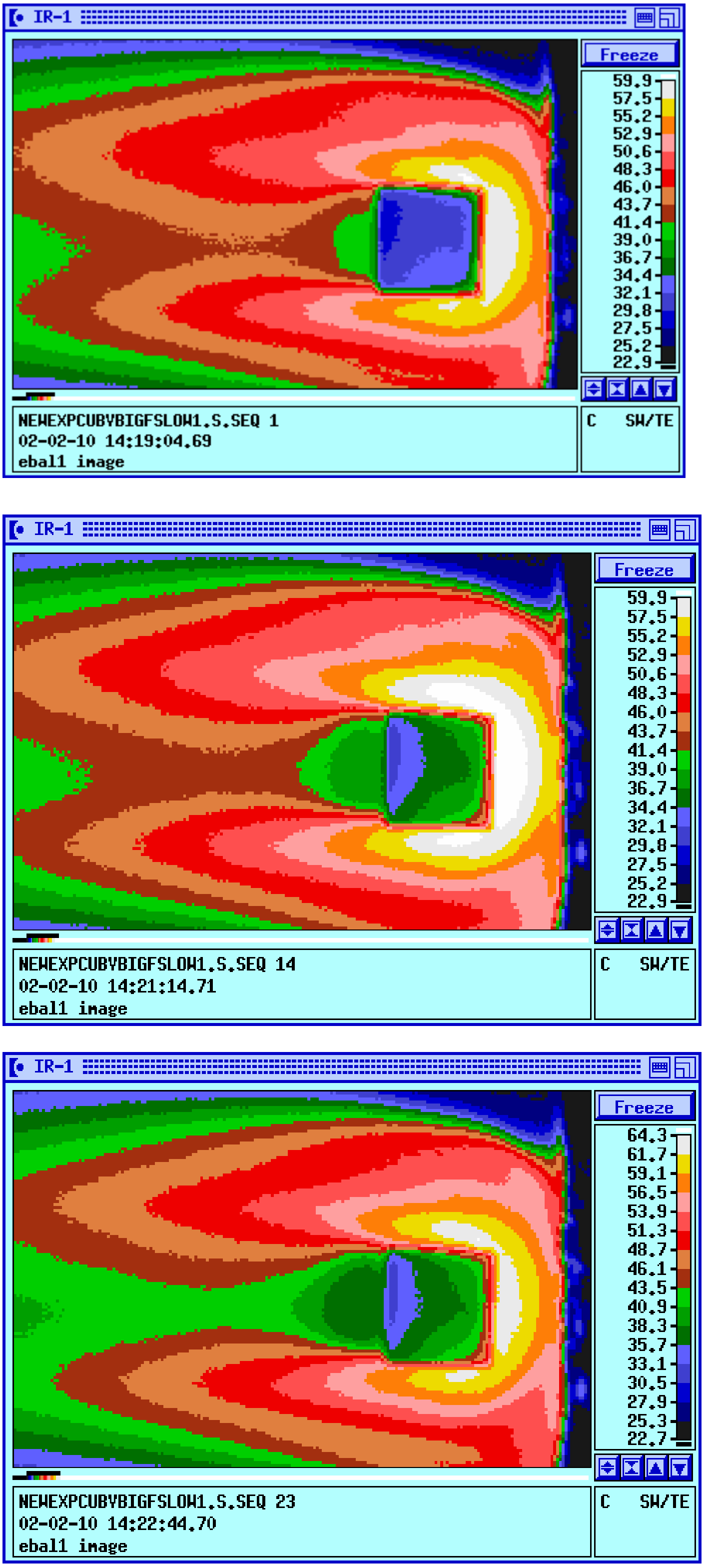
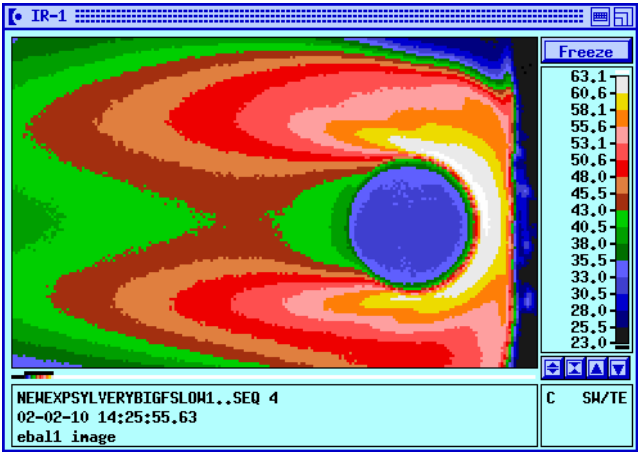


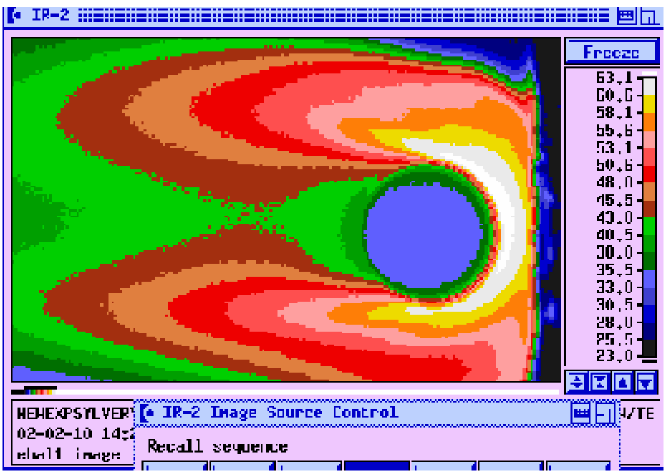
Figure 5: Flow and heat transfer visualization around a cube.

Top

A



B



C

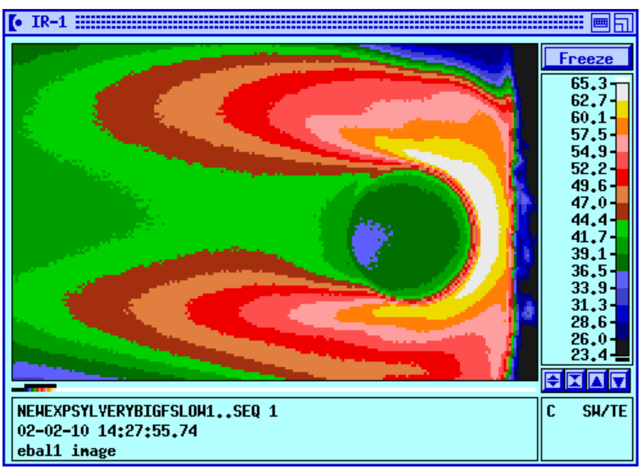


Figure 6: Flow and heat transfer visualization around a cylinder.

Top