Course Name	Optical Measurement Techniques in Thermal Science
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Course Description

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Module 1: Introduction to Experimental Techniques

Lecture 1: Role of experiments in engineering

The Lecture Contains:

Introduction to Experimental Techniques:

Introduction

Engineers are often required to design and analyze processes that involve spatial and temporal variations in the relevant parameters. Examples range from heat and mass exchangers, engines, turbines, all the way to aircrafts and submarines. In such applications, design and analysis are facilitated by experiments on a laboratory scale, so that critical phenomena can be localized and studied in detail. The present chapter surveys the conceptual framework needed to conduct dedicated, laboratory scale experiments.

The process being designed may comprise intermediate steps which are elementary, or may be in the form of a network of components that are individually simple. In each case, the system design can proceed from first principles applied to the components, wherein the model parameters are estimated from engineering handbooks. At the other end, one may encounter systems of great geometric, structural or phenomenological complexity. The first-principles approach in these cases may either work out to be too complicated or may not be possible at all. In such cases, experimental techniques become useful since the system can be subjected to a known input function and its response can be measured in real-time under reference conditions.

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Experimental techniques in engineering are generally used in the following contexts.

1. To explore system performance under a variety of input conditions. (This is also called ***process identification***)

2. To generate calibration data for parameter estimation.

3. To test hypothesis which go into building a mathematical model.

Irrespective of the final goal, experiments have to be carried out on a definite piece of hardware with all the accompanying instruments and measurement systems. For systems that are massive in size, a scaling down may be required; for those which are miniature systems a scaling up operation is required. Accordingly, the measured data will have to be scaled before being applied to the real systems. Scaling principles are often referred as *similitude*. Scaling principles can be developed in many applications by performing a dimensional analysis of the input *(controlled)* and output (*uncontrolled)* variables.

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The need to construct a physical setup gives rise to the question of cost. In many applications, the cost of instrumentation may also be quite high. Thus, the central issues such as experiments versus utilization of published data, simple and inexpensive versus complex and expensive experiments, short versus long, scaled versus prototype and detailed versus cursory experiments have to be carefully addressed. From an engineering point-of-view, economic viability will play a decisive role in the nature of experiment to be conducted.

NOTES:

1. The procedure that is needed to construct the experimental apparatus itself involves design.

2. The phrase *design of experiments* used in later sections refers not to that of the apparatus, but to the experimental procedure that will maximize the information derived.

3. Discussion on specific issues in the present chapter uses terminology that would be familiar to engineers, rather than statisticians.

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Role of Experiments in Engineering

Laboratory experiments are important for improving our understanding of physical phenomena that occur in nature as well as in engineering equipment. The present chapter discusses experimental techniques used in studies related to fluid mechanics and heat transfer.

Determination of Fluid Properties

In continuum mechanics the physical principles of mass balance and Newton's second law of motion are supplemented by constitutive relations that describe material behavior. For example, the stress-strain rate relationship for a Newtonian fluid is written as

$$\sigma_{ij} = (-p_d + \lambda \ \nabla \cdot u) \ \delta_{ij} + 2\mu\dot{\varepsilon}_{ij}$$

Here σ is the stress tensor, $\dot{\varepsilon}$ the rate of strain tensor, δ the Kronecker-delta, u the velocity vector and p_d the thermodynamics pressure. Quantities λ and μ appearing appearing in this equation are material dependent parameters and are hence fluid properties. These must be determined from simple laboratory experiments in which σ, $\dot{\varepsilon}$, u and p_d are independently known. Once λ and μ are tabulated for a variety of fluids the constitutive relation becomes a useful tool for solving engineering problems.

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Another example is Fourier's law of diffusion of thermal energy given as

$$q = -k\nabla T$$

where q is the diffusive heat flux vector, ∇T the temperature gradient and k the thermal conductivity. The usefulness of this relationship depends on the availability of the value of k of the material being studied. This property in turn must be determined from laboratory experiments.

Besides material properties, certain flows admit universal behaviour independent of the choice of the fluid. For example, in a fully developed turbulent boundary-layer the mixing length l scale as

$$l = \begin{cases} \chi y & (inner\ \ layer) \\ \lambda\delta & (outer\ \ layer) \end{cases}$$

where y is the distance from the wall, δ is boundary-layer thickness and χ and λ are universal constants that represent the state of the flow. These constants must be determined from laboratory experiments.

Experiment as an Aid to Improved Modelling

Boundary-layer theory was developed when Prandtl observed in wind tunnel experiments that velocity gradients were confined to a small layer close to the solid wall. In recent years, laboratory experiments have revealed the existence of coherent structures even in relatively continuous flows; an example is shown in Figure 1.1 for a mixing-layer. The wave-like structures of Figure 1.1 increase the amount of entrainment and substantially increase heat transfer.

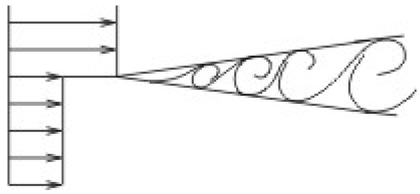

Figure 1.1: Schematic Drawing of a Mixing-layer

These examples show that experiments can bring to light unknown and unexpected phenomena and lead to the development of new theories.

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Study of Natural Phenomena and their Applications

Probes are being sent to far reaches of the atmosphere to study wind patterns, turbulence, cloud properties and the origin of this planet's climate. Similarly one cuts through various layers of earth to determine the pattern of distribution of groundwater or the presence of oil reserves. These are examples of field experiments, as against laboratory where one studies localized phenomena.

Testing of Hypothesis

One of the primary roles of laboratory experiments is to test hypotheses that are required in developing a theory. Some of the hypotheses that have been experimentally validated are:

- Linear stress-strain rate relation for commonly occurring fluids such as air, water and thin oils.
- Mixing-length hypothesis for a fully developed turbulent boundary-layer.
- Onset of transition in boundary-layers in the form of two-dimensional periodic disturbances.
- Mathematical analogy between convective heat and mass transfer.

Experimental confirmation of approximations is a vital confidence-building measure that posits reliability to modeling and analysis of real-life engineering systems.

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Layout of a Fluid Flow Experiment

An experimental setup consists of certain essential elements which enable the measurement of physical quantities such as velocity, pressure and temperature at distinct locations in the flow domain. The physical domain is a fluid region in which velocity, pressure and temperature fields are present. The fields vary in general from point to point and with time. A probe is located in the flow and its state is altered corresponding to changes in the flow quantity to be measured. In principle the probe does not affect the flow itself. The measurement system senses the altered state of the probe and generates a signal that can be understood by the observer. Alternatively, it produces an electrical signal, which can be amplified, filtered and digitized by a signal analyzer. This signal can be conveniently displayed on an output device such as voltmeter or stored in a computer for data processing. Usually the observer receives the output of a probe as an electrical voltage generated by the measurement system. When the output of the probe is an electrical signal it is called a transducer.

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The curve or a relationship connecting the voltage to the local fluid velocity or pressure is called a calibration curve. The layout of an experimental setup is shown in Figure 1.2. Present-day experimental setups replace the data storage unit by a computer that not only stores data but can begin and end the experiment itself .

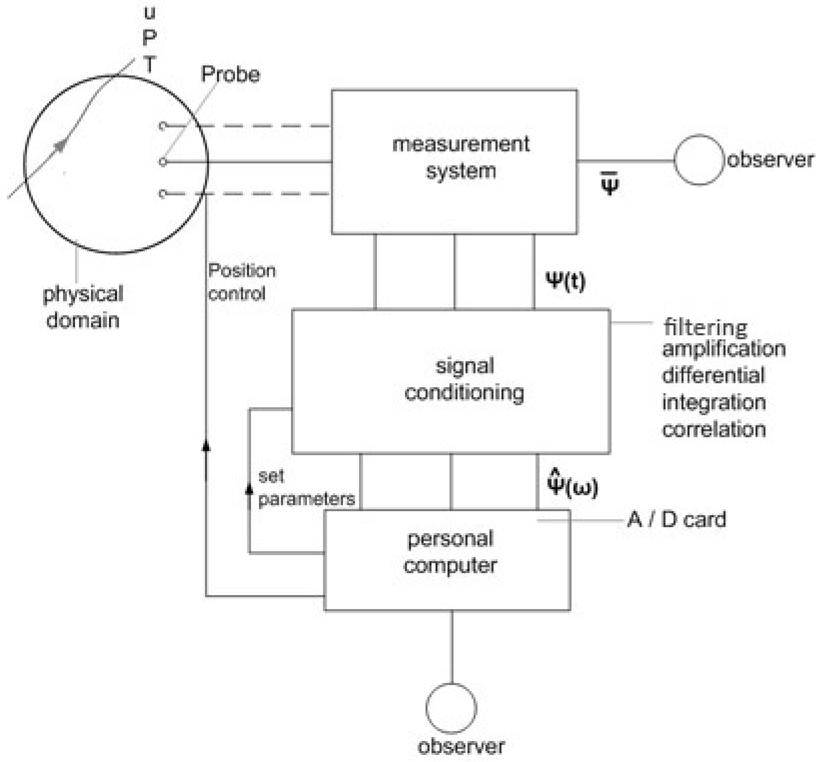

Figure 1.2: Schematic Drawing of an Experimental Setup.

An example of a calibration curve for a hot-wire anemometer is shown in Figure 1.3. It is natural for the flow to have a certain amount of fluctuation, say u' superimposed on a mean value u This will manifest as a fluctuation e on the volatge E generated in the experimental setup. The relationship between e and u' is determinded as follows: From the calibration curve, we have

$$u = f(E)$$

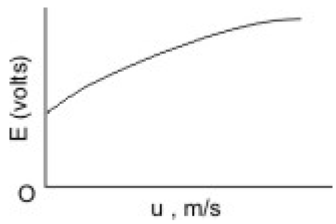

Figure 1.3: Example of a Calibration Curve.

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Applying Taylor's series approximation for a small change in the value of u

$$u + \Delta u \approx f(E) + \left.\frac{df}{dE}\right|_u \Delta E$$

where the series has been truncated after the first term. Setting $\Delta u = u'$ and $\Delta E = e$, we get

$$u' \approx \frac{df}{dE} e$$

Here, the quantity df/dE is the gradient of the calibration curve evaluated at the operating point $(u = f(E), E)$. The error due to truncating the Taylor series is usually small if $|u'/u| < 0.1$. The truncation error in calculating u' can be reduced by working with an extended Taylor's series expansion

$$u + \Delta u \approx f(E) + \left.\frac{df}{dE}\right|_u \Delta E + \left.\frac{d^2 f}{dE^2}\right|_u \frac{(\Delta E)^2}{2!}$$

wherein the higher order term $(d^2 f/dE^2)\ (e)^2/2!$ has been included. This approach is useful provided the higher order derivative can be determined accurately. In practice, the calibration curve is experimentally constructed and these higher order derivatives can be computed only with substantial error.

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