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Computer Aided Experimentation in Engineering*

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Experimentation is a key component of any engineering education. The philosophy and psychology of an experiment is the central theme of this paper, which aims to illustrate how education through experiments may be improved by the judicious use of stimulation of laboratory experiments on digital computers. The paper addresses the role of experimentation in the development of science and reviews the definitions of science and scientific knowledge before discussing the process of validation of the scientific knowledge. The validation processes have been reviewed in order to highlight the role of experimentation further. A number of recommendations are made for more efficient and effective laboratory practice and their practical implementation is illustrated by an example of a computer-aided experimental program HEATO. The program has been developed first for practising the activities of scientists and methods of validations on a computer-aided experimentation environment and second for simulating an experiment on heat transfer for flow in a pipe.

1. INTRODUCTION

EXPERIMENTATION and model building are important methods of advancing scientific knowledge. Advancement of scientific knowledge through solution of models using the rules of mathematics have practically dominated the last four decades. Although it is widely recognized, that experimentation is an important activity in academic science, it is not clear to many students that an experimental course forms an important part of their educational curricula. During this period a large proportion of laboratory equipment for teaching fundamental science especially in engineering institutions has become out of date and there is little evidence of willingness towards replacement or expansion of laboratories. Moreover in UK universities, due to increase in the student/experiment ratio only a small percentage of students in any group activities take part in performing the experiment. In order to highlight the role of experimentation in scientific research, the activities of scientists will be reviewed and the different processes of scientific knowledge validation will be discussed. Moreover, by introducing the idea of computer-aided experimentation, it will be shown how computers can be used to enhance the understanding of the scientific phenomena and reduce the deficiencies in the existing laboratories to a large extent.

2. SCIENCE

Conventional definitions of science tend to reflect different features of science. The *problem solving aspect* of science emphasizes its instrumental aspect, that is it views science as closely connected with technology. The *organized body of knowledge* concentrates on the archival aspect of knowledge; that is, acquisition of the body of knowledge about natural phenomena, their organization into theoretical schemes and their publications in books and journals. The *methodological aspect of science* emphasizes procedures such as experimentation and observation that are elements of a method for obtaining reliable information about the natural world. The *vocational aspect of science* emphasizes the definition of whatever is discovered by special people. This draws attention to mental attitude which is commonly described as a scientific frame of mind. Perhaps the best account of a scientific mind is to be found in F. Bacon's [1] description of himself

> a mind nimble and versatile enough to catch the resemblance of things which is the chief point and at the same time, steady enough to fix and distinguish their subtle differences; . . . endowed by nature with the desire to seek, the patience to

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> doubt, fondness to mediate, slowness to assert, readiness to reconsider, carefulness to dispose and set in order and . . . neither affecting what is new nor admiring what is old and hating every kind of imposture.

The above definitions of science are complementary and they can be connected as shown in Fig. 1. For further details see Campbell [2]. In the last four decades the whole field of scientific studies has been transformed by the realization that science can only be understood if it is treated as a social institution both within its own sphere of activity and its relationships with the world at large. The sociology of science can be divided into two parts: (a) academic science which is the characteristic model for the internal sociology of science, and (b) external science where the academic science core is treated as a black box whose internal mechanisms can be ignored. That is, study is concentrated on the technological effects of knowledge that has percolated outward and then been applied to the solution of practical problems as shown in Fig. 2. The traditional way of studying science has three distinct psychological, philosophical sociological aspects:

1. The psychology of science uses personal terms, such as motives, perceptions and intelligence.
2. The philosophy of science uses types of knowledge such as contradiction, theories and hypotheses.
3. The sociology of science considers the communities with institutions, norms and interest.

Each of these schemes has been develolped independently in its own dimension up to a high level of intellectual sophistication. However, science is a complex activity and cannot be understood thoroughly without consideration of interrelations among these activities. For further details see Achinstein [3].

The next question is: what are the distinguishing features of scientific knowledge? This traditional philosophical question is important because it may decisively affect our actions to know that a particular piece of information is scientifically warranted. It also asks about the fundamental objectives of research. For example, if the goal of science is to make discoveries, then one must know what a scientific discovery is. Moreover, if one insists that scientific knowledge is only to be gained by a special method, then one would enquire whether this method makes the knowledge particularly valid. For further details see Russell [4].

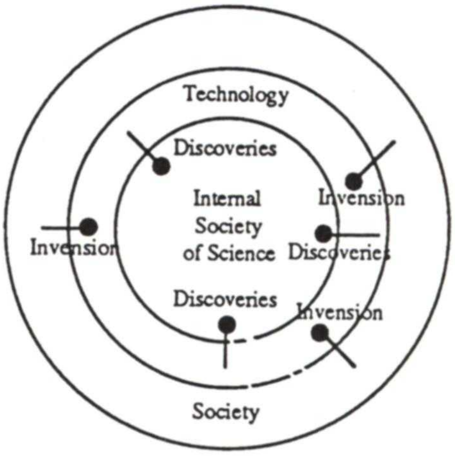

Fig. 2. Different layers of science

Academic science can be defined as a social institution devoted to the construction of a rational consensus of opinion over the widest possible field. It is a characterization which every word is open to question, criticism and empirical testing. It provides an active principle by which many observed features of the academic style can be linked together. The obvious archival, methodological and vocational features of science can be related to it without a major inconsistency. In any case, whether or not one accepts maximum rational consensus as the fundamental objective of academic science, the principle is convenient as a provisional hypothesis around which scientists really work. All definitions for academic science refer to knowledge of some aspect of the world, that is, science appears to take the existence of the external world for granted. This is by no means a trivial consideration, no philosopher has been able to show that such a belief can be achieved by argument alone. Experience shows that for tackling any problem some sort of intuitive or instinctive leap becomes necessary as a basis upon which reason can be applied.

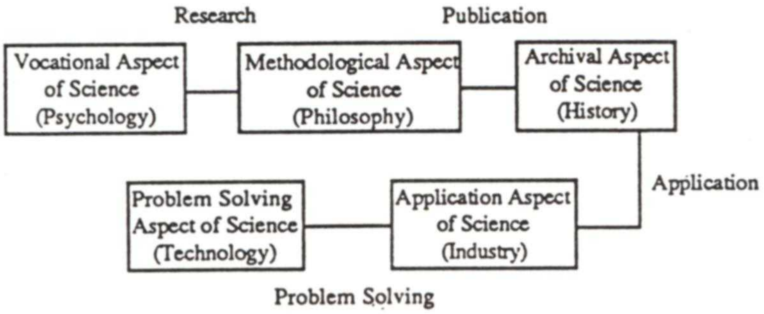

Fig. 1. Connection of different definition of science

3. SCIENTIFIC RESEARCH

A summary of activities which scientists are engaged in the research process are as follows:

3.1 *Investigation*

The aim of science is not only the accumulation of factual information, but it is to acquire knowledge in the form of significant general patterns of fact. Out of potentially observable and scientifically accurate facts very few are distinct and simple enough to be fitted directly into a well-structured classification scheme. Scientific research is therefore directed towards acquiring the special type of information that is likely to contribute to this endeavour. As the classification scheme is extended to cover more and more members and classes of members, increasing attention must be given to the ordering principle by which it is organized. In the development of any scientific discipline there are phases of exploration, where new information becomes available which will be recorded with little regard for its ultimate scientific value. The most effective strategy of research is purposeful investigation, that is, deliberate study of the circumstances that are thought to relate to an existing idea. This takes the form of formulating specific questions and then seeking for information needed to answer them. The history of science shows that many scientific discoveries have been made by chance or in the course of unscientific activity. Occasionally, an observation is made which seems relevant to a question that was not consciously in mind at that time but has led to a significant scientific discovery by further investigation. In modern physics the primary facts of nature are events which are ordered in time and space in patterns derived from strict mathematical principles. For more details see Beveridge [5].

3.2 *Observation and instrumentation*

A large number of scientific disciplines have only been made possible by the development of devices that extend human perception into inaccessible domains. The notion of observation has been expanded with the invention of more elaborate instruments which are almost free from observer bias. For example, an infra-red telescope makes visual representations of patterns of electrical signals that could never be detected directly by human eye. However, every scientific instrument is susceptible to the criticisms originally made to Galileo's telescope, that the strange objects seen through it were not really there but were merely artefacts of the instrument itself. That is, the characteristics of the instruments used in research cannot be dissociated from the events observed with those instruments. The term observation has expanded metaphorically, far beyond the generation of images for direct visual inspection and spatial interpretation. Of course any instrument has its own characteristic defects which may introduce random or systematic errors into its output. However, such defects can often be reduced to a negligible proportion by deliberate redesign. For further details see Dove [6].

3.3 *Measurements and computational methods*

The transition from integral measures to continuous is far from trivial from practical and logical points of view. All human sensations tend to be somewhat irrational and so humans accept themselves as unreliable measuring devices compared with real instruments. Instruments are often used to make measurements, that is, they present the results of their operation in numerical form. Measuring instruments have become more and more sophisticated so that, it is now possible to measure a vast range of properties to a great degree of precision. In any scientific discipline one of the prime objectives is to discover what relevant aspects of nature can be described quantitatively. The science of physics is dominated by the theory of measurement. Lord Kelvin is reported to have said

> when you can measure what you are speaking about and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely, in your thoughts, advanced to the stage of science.

Of course this is not to say that all qualitative classification schemes are scientifically inferior to quantitative ones, it just means that an observational account in numerical terms is more effective as a means of discovering significant patterns in the natural world. By choosing to represent the natural world in numerical terms, descriptions have been brought into the domain of mathematics. That is, if one can find satisfactory empirical meaning for various abstract mathematical relations, then it is possible to manipulate the data mathematically to generate more new facts that were not directly observed. Southwell [7], a pioneer in the application of calculation by numerical analysis to engineering problems, stressed the importance of understanding experiments from which the data is obtained, when he wrote that 'computational methods should allow for the margin of uncertainty which is there in practice whether we like it or not. A calculation is only as accurate as the experimental data fed into it'. This dependence of analysis upon experimental data can be quite critical. It has been found to be particularly so in design studies that seek an optimized solution. Prospective theoretical scientists are reminded that the work of many theoreticians has been hampered by their lack of appreciation of experimental results. In a classic example, Newton postponed the publication of his theory of gravitation for 20 years, because there was a discrepancy of about 10% between the measured value for the acceleration of the moon and the value postulated by his theory. It apparently did not occur to Newton that the experimental value for the radius of the earth, which he used in his calculation, could be in error to this extent.

3.4 *Experiment and its features*

Scientific investigation is not limited to the study of natural phenomena. Modern science is largely founded on the results of experiments, where the natural world is deliberately interfered with in order to observe the consequences. Of course for disciplines whose significant events are remote or inaccessible in space and time, this method of investigation is not applicable. An experiment has the following features:

1. It is empirical, it is performed in the real world, in real time, on real objects and gives factual results.
2. It differs from a mere observation in that it is contrived. An experiment embodies organized observation in a sense that the events to be studied are made to occur as far as possible under carefully controlled circumstances. It has a rational purpose such as observing a phenomenon or exploring an unknown domain.
3. A true experiment must be in some sense original. In an ideal form it is supposed to generate new information through a novel experience not previously seen in science. Many experiments are designed to replicate previous ones and to check that their results are reproducible. However, practical science education which is largely based on standard laboratory experiments will not qualify since their outcome is not in doubt. For further details see Munce [8].

3.5 *Description*

Scientific information is essentially descriptive. According to the conventional metaphor, scientists explore the natural world and endeavour to describe it as it is. However, a scientific description of an event is not just any account of something experienced. It is also expected to conform to certain canons of accuracy, completeness and reliability. Although the criteria for such qualities are difficult to define, they are already available by convention in any recognized scientific discipline. They define the characteristics of facts on that branch of science. The facts can only be acquired by patient and systematic observation.

3.6 *Generality*

The essence of scientific knowledge is to encompass particular facts into general statements. In science, general statements are no less factual than their individual elements. A great deal of scientific effort is therefore devoted to the task of devising well-defined classes of events. The essential question is by what criteria is it advisable to treat certain individual events as practically equivalent to one another and at the same time as different from one another? The significance of names used for referring to whole categories of individual items is one of the oldest issues of philosophy, applying in principle to all uses of language. Is it a fact that two classes can be distinguished unequivocally by reference to simple standard criteria? The prime example of this type of scientific work is identification and classification of mineral specimens, which is one of the factual foundations of mining engineering.

3.7 *Scientific laws*

Research is directed towards the discovery of patterns of classification whose structural principles can be stated clearly. The regularity that might be noticed in a set of facts or events is invariant association which reduces significantly the amount of details required in describing the world. When a regularity is considered to be highly significant for science, it is referred to as a law of nature. Scientific laws are formulated in different ways, that is, they may specify the results of lengthy observations or the outcome of some contrived experiment. In science a law denotes a definite association between observable empirical features of natural phenomena. There is nothing clear about this distinction. Some laws such as Newton's laws of motion and laws of thermodynamics apply to facts that are far from being directly observable. There are two main classes of scientific laws:

1. Laws of substance which describe the invariable properties of materials and systems that occur in nature. For example, at one time two invariable properties of water were thought to be the freezing and boiling points. Although later investigation showed that pressure may have a significant effect on these properties, one can never be certain that other factors have not been omitted.
2. Laws of function describe the invariable relations that exist between the properties or materials and systems. Traditionally, laws of function concerned with relation between cause and effect, if one event occurs then another event will invariably follow. However, many laws of function really involve not so much the idea of causal sequence through time but that of specific numerical relations. There are still interesting questions to be answered: (a) are scientific laws discovered or constructed? (b) are some laws more fundamental than others? (c) are the regularities described by scientific laws produced by chance or are they somehow essential?

For further details see Durbin [9].

3.8 *Explanation*

It is universally accepted that one of the major goals of science is to explain the facts and events of nature and the laws governing them. It is a rational argument linking an assembly of empirical facts with a general conceptual scheme. Thus, any well-formulated scientific law may be counted as a step towards explaining the observation that it sets in order. A much more convincing type of scientific explanation is one that links a generalized class of facts with an intellectual structure derived from a different empirical domain. Ideally, the explanatory relationship should be strictly logical. There are many examples where the explanation is a direct deduction of a special case from a general covering law. For example, Kepler's laws can be derived from Newton's laws of motion and the Principle of Universal Gravitation. For further details see Braithwaite [10].

3.9 *Models*

The results of a scientific investigation are usually too diverse to fall into regular patterns. Although it is possible to produce a set of interrelating laws to express all the regularities and irregularities that have been observed, the scheme would become too complicated to accept it as a satisfactory explanation. The most fruitful source of explanatory schemes in science is analogy. That is, it is often possible to produce a satisfactory account of a body of scientific facts by reference to a model. The notion of scientific model is very broad. It can be defined as a real or imaginary system whose structure is similar to the system under investigation. Undoubtedly, a model can provide explanations to a large number of observed facts or events. In physical science, models are often so well-defined that their behaviour can be analysed mathematically. The notion of the model extends to a purely symbolic domain, where there is only an abstract similarity between the original system and its model. For further details see Andrews [11].

3.10 *Theory*

While there is something close to universal agreement among individuals concerning scientific laws, this is seldom the case with scientific theories. The reason for the difference is that laws in general can be confirmed empirically by an observer, whereas scientific theories which explain the general classes of observational and experimental facts are not so accessible to direct test by perception. A well-founded theory, covering a wide range of facts to a high degree of accuracy is the most compact form in which scientific information can be recorded, manipulated, used and understood. It is a medium by which a description of natural phenomena is expressed as scientific knowledge. Theories belong to the world of ideas and can only be expressed or communicated in symbolic form such as words, mathematical formulae or diagrams. In contrast to a law, a scientific theory is somehow a human artefact. They assert structural relationships between concepts which can be further manipulated in abstraction according to logic or other laws of thought. There are two extreme views of the status of scientific theories:

1. The concepts employed in theories are typically fictions, they are instruments which support the imagination and guide predictions.
2. The theoretical entities do refer to real things, that is the entities can be shown to exist if appropriate techniques can be found for doing so.

There are broad characteristics of a satisfactory scientific theory:

1. A scientific theory must be rational, that is, it must be logical and without obvious inner contradiction. In practice this is a strong condition, since it is not always easy to prove self-consistency of closely related formal propositions or mathematical equations.
2. A scientific theory must be relevant. An articulated and self-consistent structure of abstract entities is of no scientific interest unless it is accompanied by interpretative principles relating it to the empirical world.
3. A scientific theory must be extensible, it should explain more facts than it was originally intended to do.

A suitable theoretical structure may often be adopted from some other discipline. Theory building by analogy transfers models and other conceptual entities from one branch of science to another. For further details see Bunge [12].

3.11 *Conjecture and hypotheses*

A new theory which has not been subjected to the rigorous process of substantiation is referred to as a hypothesis. It may even present itself as conjecture, suggesting a possible conceptual relationship without immediate concern for consistency with other theoretical principles. The sequence from conjecture through hypothesis to theory suggests an increasing degree of coherence and scientific certainty. The next step is to subject the hypothesis to further analysis to test how well it fits into what is known or might be found out, that is:

1. Are there other known facts which it might explain or with which it might be inconsistent?
2. Does it explain all the facts for which it was originally conceived?
3. Could an experimental work be devised to observe these implications?
4. To what extent is it logically consistent with other well-known theories?

For further details see Durbin [9].

4. VALIDITY

The fundamental concern of epistemology is how much of the scientific knowledge can be considered true or how firmly it should be believed. The history of science rejects any notion that all scientific knowledge is true. Scientific knowledge contradicts itself from generation to generation, that is, it cannot be true at all time. In practice science is always prone to error and always open to corrections. The activities outlined in the previous section do not provide a technique for generating absolute truth. The credibility of a particular item of scientific theory depends upon the extent to which it has been subjected to tests and not found defective. The central epistemological question is whether there is a method by which a scientific theory can be made perfectly certain?

4.1 *Method of empiricism*

A great deal of what is reported as scientific information is factual in the ordinary sense of empirical truth. This suggests a standard of credibility which all scientific information would eventually attain. Whatever philosophers may doubt, most scientists would be entirely satisfied if all science could achieve the epistemological status of empirical truth. In science a deliberate effort is made to eliminate some of the known imperfections of human perception and observation. The practical methodologies of research are directed against two major sources of empirical uncertainty:

1. Although human perception is remarkably sensitive and discriminating, it is easily affected by mental factors. Therefore, in science automatically recorded data and photographs replace the scientist's memory and hand-drawn sketches. Use of these devices can remove the phenomenon of subjectivity to some extent. In reality, there is always an element of human interference in the design and the interpretation of data produced by these devices. The best that scientific methodology can do is to neutralize subjective factors by playing off one human observer against another.
2. Science has little use for unique events or objects that cannot be classified according to some rational principle. It is essential to be able to show that the facts of interest are reproducible. This would be impossible if significant differences between individual specimens are produced by chance. In general, facts collected by passive observation are less certain than the results of contrived experiments which can be designed to minimize accidental influences on the course of events. However, scientific errors can arise from uncontrolled variations in the external conditions. This can be so serious that it is usual to replicate the experiment before concluding that its results are truly reproducible. The aim of empiricism is to assemble a body of strictly factual observations whose validity can be made secure by procedures derived from daily common sense and theories can be constructed based on these facts. From *Memoirs of Sherlock Holmes* by A. Conan Doyle:

> 'This is indeed a mystery' remarked Watson, 'what do you imagine that it means?'
> 'I have no data yet, it is a capital mistake to theorise before one has data. Insensibly, one begins to twist facts to suit theories, instead of theories to suit facts'.

The strict separation of theory from experiment was the cornerstone of the Carnap [13] program to reconstruct science on a purely logical basis. Since observations expressed in a special language can be translated into an idiom devoid of theoretical terms, it can act as the universal, neutral arbiter among alternative hypotheses. It is now generally agreed that there is no such thing as purely observational facts and empirical scientific observations are heavily theory laden. Namely, the method and circumstances under which an observation is made cannot be described accurately without reference to other scientific facts. However, some philosophers have argued that the distinction between theory and observation can be possible in principle by expressing all complex observational statements in terms of direct experienced events. This may prove to be impractical because of the immense circumlocution required to describe the simplest scientific event. For further details see Smart [14] or Topping [15].

4.2 *Method of induction*

An induction is a general proposition in the form of a question derived from particular data. The question itself proposes a generalization and induction endeavours to secure the elicitation of truth from the disclosures of experience. The difficulty is that a general proposition does not follow by rigorous logic from a finite number of particular instances, since the general proposition cannot be tested empirically for all its possible cases. It is essential to understand that no proposition derived in this way can ever be conclusively verified. This is a serious problem, since there are numerous cases in the history of science where confirmed empirical generalizations have later been unconfirmed by contrary instances. As D. Hume (1711–76) stressed, it is impossible to verify that the laws of causality will operate in the future as they have operated in the past. Therefore, inductivism is not satisfactory as a fundamental scientific epistemology. There is always an element of insecurity and uncertainty in the justification of scientific knowledge. Bacon's method was the exhaustive collection of information about the world followed by generalization. Bacon was certainly aware of the problems of inadequate information and it was this awareness that prompted him to collect more and more evidence before daring to proceed to the generalizing stage of his method. He was so dedicated to the advancement of learning, which prevented him from seeing a role for the hypothesis or informed guess with its attendant risk of error. For further details see Peirce [16]. Modern philosophers think that inductivism is fatally flawed as a methodology by the following arguments.

1. The inductivist claims that observation can be a sure basis for scientific knowledge. This idea assumes that the human eye works like a camera and that the observer sees whatever is projected on to the retina. The point is that what one sees depends only in part on the immediate sensory

experience, but also in part on accumulated past experience and on expectation. That is observation is not objective.

2. Several observers viewing one object will formulate different observational statements about their experience. That is, their public statements cannot be expressed without reference to prior theoretical understanding. This shows not only that observations are preceded by theories, but also the reliability of the observations will inevitably be determined by the reliability of the theories upon which they depend. In order to verify an observation statement one should appeal to our theoretical knowledge, not to a more basic observational statement. However, since theories are fallible, observation statements cannot be on an infallible basis for scientific knowledge.

3. Even if inductive generalizations could be proved sound, its conclusions would be no more secure than its initial observational data. There is no rule which can tell us when sufficient observation statements have been collected to justify the generalization. One cannot know what kind of variety of observations to make without prior theoretical knowledge. Moreover, one cannot know whether an observation which contradicts a universal law actually counts without a theoretical background.

4.3 *Deduction*

Unlike induction, which is the generalization process from a finite number of particular instances, deduction is the demonstration of particular instances from a general proposition. A deductive argument involves the idea of conclusive evidence or proof. Accepting an argument as deductively valid does not of course mean that the conclusion is necessarily true. This will be the case only if the premises are also true. One way of revealing an invalid argument is the method of counter example. That is, the argument being tested is compared with another argument having the same form, but in which the premises are known to be true and the conclusion false. Mathematics is a typical deductive science in which all the theorems are necessary consequences of the axioms. There is indeed a method of mathematical induction, but the name is unfortunate since it suggests some kinship with the methods of experimentation and verification of hypotheses employed in the natural sciences. But there is no such kinship and mathematical induction is a purely demonstrative method. It is necessary to caution the reader against the common error of confounding the temporal order of discovering the propositions and the order of their dependence. For example, in geometry there is a preparatory stage in which one guesses, speculates, draws auxiliary lines and so on until the proof is discovered. However, no one should confuse the preparatory stage with the proof finally achieved. Initial search has indeed close kinship in any field with human investigation. The process of testing, guessing and search characterizes research in mathematics as well as research in mathematical science and proof using the principle of mathematical induction is perfectly rigorous, deductive and altogether formal. For further technical details see Nidditch [17].

4.4 *Prediction*

A convincing demonstration of the validity of a scientific hypothesis is the successful prediction of a previously unobserved or unrecorded phenomenon. Predictions are not necessary and sufficient conditions for scientific explanations. There are reliable sciences whose phenomena cannot be strictly predicted since they all occurred in the past. However, theories about these phenomena may be validated by the discovery of predicted evidence after they were originally proposed. The success of scientific prediction must surely strengthen the credibility of the hypothesis on which it was based, but this does not mean that a hypothesis is made certain when its prediction is confirmed. On the other hand if a particular test fails to prove its predicted result, this would be extremely significant.

4.5 *The hypothetical deductive method*

There is no doubt that the advance in growth of knowledge that has come in more recent times is the result, not just of exhaustive collection of factual material and generalizations, but rather of a radically new approach known as the hypothetico deductive method. The two-phase process of validating hypotheses is the essence of this method. The phases are:

1. The prediction phase is essentially theoretical, that is, a theory should be clearly stated and open to formal logical analysis. Verbal and mathematical arguments can be applied to extend its scope and to deduce various empirically observable consequences. Any ambiguity, imprecision or inconsistency in the chain of argument leading from the hypothesis to its implications can give rise to errors in the validation process.
2. The confirmation phase addresses the question of whether the facts fit the theory. This is the realm of experiment, it is dominated by the use of sensitive instruments to make accurate measurements.

It is obvious that the method involves setting up a generalization by induction from empirical observations and then seeking confirming instances of its predictions. That is, a trial and error process. The move towards this method was started by Whewell [18]. He examined in great detail the role played by observation and experiment, most significantly the idea of happy guesses in the advance of scientific knowledge. The most influential advocate of this methodology has been Popper. Popper's [19, 20] views were first published in 1934 and translated into English in 1959. His [21] more recent book encapsulates the essentials of his method of falsification. His principle goes beyond asserting that every inductive generalization is logically fallible and that scientific hypotheses can be corroborated but can never be absolutely confirmed by successful predictions. Popper's principle is extremely influential in the contemporary philosophy of science. It also suggests a rationale for the research strategy of testing theoretical predictions that otherwise is unlikely to be confirmed. If against the odds the trial is successful, the credibility of the theory will rise from a small value to something approaching certainty. Although in modern terminology the method is described as hypothetico deductive, it is essential to note that the process of testing scientific hypotheses has been inductive. Namely, when a hypothesis is tested and not falsified, the evidence for the acceptance is not deductively conclusive in the way of mathematical argument. Unfortunately, it is not always a simple matter to decide whether a theory has been falsified:

1. Any hypothesis under test is bound to rely upon one or more additional hypotheses which have already been tested independently. Despite their wide acceptance, the additional hypotheses are not certain. Therefore, in determining the logical status of the hypothesis under investigation it can never be known whether this or the additional hypothesis is confirmed or refuted. For further details see Duhan [22].
2. If a theory has been falsified, it is difficult to distinguish between a falsification at the level of logic and the level of methodology. A famous example was that the planet Uranus did not follow the orbital path predicted by Newton's equations. At the time rather than rejecting Newton's work it was boldly predicted another planet was responsible for this and this led to the discovery of Neptune.

According to falsificationists, scientists should never resort merely to *ad hoc* defences and the best way to ensure against this is to welcome the falsification of a theory as evidence of something far more important, that is the growth of scientific knowledge. However, the falsification method also has its limitations:

1. If a scientific theory is proved to be false, one cannot be sure whether the theory of one of the additional hypotheses is at least false.
2. The falsification method implies that, there is an essential qualitative distinction between the attempt to verify and the attempt to falsify. However, the case against inductivism can be turned against the falsificationist in the same way. That is, if an observational prediction of a theory indicates that the theory has been falsified, this can only be true if the observation statement itself is reliable. However, wholly reliable observation statements are not available; therefore, there is no way of telling whether theory or the observation statement is false.

Kuhn [23] elaborates on the inertia of belief by invoking another psychological experiment. In this way prior expectations can lock the experimenter into a particular way of viewing the world of empirical phenomena. Similarly, a researcher looking at a group of experimental results before a radical theoretical change sees a very different state of affairs from the scientist looking at the same results afterwards. In recent years there have been many other points of view regarding the scientific methods (for further details see Lakatos [24] and Feyerabend [25]).

5. AIMS AND PSYCHOLOGY OF EXPERIMENTS

The psychological aspects of a laboratory environment are also important and should be included in the computer-aided environment. In the following section a summary of these activities will be outlined:

1. Laboratory experience establishes an organizational frame, that is students soon learn that, the success of an experiment depend directly upon the extent and depth of the relevant thought and planning undertaken prior attempting to make quantitative measures.
2. Laboratory experience establishes a quantitative frame of reference for physical phenomena and theories which have been accepted via lectures and textbooks. Unlike in lectures students will not be spoon-fed, but rather encouraged to make decisions themselves which are about real problems not having clear-cut answers like those of academic exercises.
3. As a result of resolving problems involving uncertainty and compromise students will soon develop self-confidence. Nevertheless, laboratory experience is mainly a matter of self-tuition by developing personal powers of observation, judgement and communication.
4. In most of the higher education institutions, experiments have specially been selected and placed in a logical sequence of gradually increasing difficulty, starting with the closed-ended and progressing to the open-ended experiments. A valuable part of laboratory studies is the development of personal judgement so as to avoid spending too much time on an experiment before proceeding to the next.
5. In performing experiments students will soon realize the truth of Parkinson's law: *Work expands to fill the time available for its completion*.
6. Experiments may appear to be dull set routine assignments, which have to be completed in order to gain sufficient marks to satisfy examiners. This results in many first year

students having a fundamental misconception about practical classes. That is, to obtain the correct answer for an experiment is all important.

It has already been stated that, experiments are ordered activities which form basic foundations for constructing analytical models in engineering. In teaching there are three aims for experimentation:

1. To illustrate a phenomenon described in lectures.
2. For building of analytical models as a basis for the design study.
3. To provide experience in techniques of experimentation.

All three are an important part of a complete course of study in the experimental method. Although the aims of these experiments are different, they do have much in common.

6. RECOMMENDED LABORATORY PROCEDURE

The steps of a common procedure for performing laboratory experiments can be summarized as follows.

6.1 *Step 1*

A copy of the appropriate instruction manual should be obtained from the laboratory when the experiment is booked. These manuals merely suggest the necessary observations and outline a method of analysing the experimental data. Often, only the required formulae are quoted in the instructions, because students are expected to understand the appropriate theoretical reasoning prior to the laboratory class.

6.2 *Step 2*

A literature survey should be conducted and a set of brief notes from stated references must be made in the laboratory diary. The process of searching for information is an important part of the training. The extent of the search is dictated by the experiment. For a first year undergraduate experiment, it may just involve reading a recommended section of a textbook, possibly taking an hour or less. However, for a research project the literature survey may well require 3 months consideration and a large number of references.

6.3 *Step 3*

The apparatus should be set up in a tidy manner and the measurements must be entered in the diary. A dummy run is recommended in order to appreciate the difficulties and sources of inaccuracy.

6.4 *Step 4*

The experimental rig should be described by means of a well-labelled diagram.

6.5 *Step 5*

Observations should be recorded immediately, together with estimates of the accuracy of all readings. If students are forced to work in a group due to shortage of experimental equipment, every student should make separate observations and evaluate the results independently.

6.6 *Step 6*

If possible, the required graphs should be plotted at the time of recording the results. By doing so the attention will be drawn to interesting trends: in the event of any rogue points or peculiarities, the relevant observations can then be checked immediately.

6.7 *Step 7*

Brief details of any difficulties and methods of overcoming should be given in the laboratory diary. Also reasons for any changes of procedure for improving the experimental arrangement should be provided.

6.8 *Step 8*

Results and estimate of the overall accuracy of the experiment should be evaluated.

6.9 *Step 9*

If the deduced results from the experiment disagrees more than those attributed to expected inaccuracies of measurement, their sources should be traced.

6.10 *Step 10*

The conclusions of the investigation should be stated in the laboratory diary.

6.11 *Step 11*

The laboratory diary should be presented for assessment well before the next laboratory class and the technical report should be prepared.

7. COMPUTER-AIDED EXPERIMENTATION ENVIRONMENT

The aims of developing computer-aided experimentation environments are as follows:

1. *Research environment*. A computer-aided experimentation environment can simulate all the activities of the scientists which were outlined in more detail in section 3. In any particular environment. That is, students can become involved in the process of investigation, observation, measurement, use of computational methods, familiarity with different types of errors, performing experiments, describing their observations, generalizing their observations, creating laws and theories and assembling mathematical models.

2. *Validation process*. A computer-aided environment can be used for practising the validation process which was described in more detail in

section 4. That is the methods of empiricism, induction, deduction and falsification can be practised by means of a pseudo random generator built into these environments. These activities can be extended by displaying the solution of more complete mathematical models and comparing them with the solution of simpler models.

3. *Inclusion of psychological aspects*. The psychological aspects of real experimentation can also be included to some extent in the computer-aided experimentation environment. That is, some aspects of the issues outlined in section 6 can also be observed.

4. *Methodology of the experimentation*. If all the steps specified above were performed properly, then there would have been no need for any alternative method of computer-aided experimentation. However, as it was explained above the reality is different and due to shortage of time, lack of interest and inadequacy of equipment the above steps are never executed thoroughly. Therefore, computer-aided experimentation can prove to be a valuable tool for reducing some of the above problems. Furthermore, computer-aided experimentation software can generally be used as an educational tool in the following circumstances: (a) if the equipment is not available either due to cost or a fault in part of the system, (b) if setting the system up is complicated and time consuming, (c) if the experiment requires excessive time for collecting data from different parts of the system, (d) if the evaluation of the results are excessively time consuming, (e) if the experiment is too dangerous to perform, (f) if the experiment is more productive by performing it many times, (g) if large inaccuracies in measuring equipment can make the final results of the experiment worthless.

Students are sometimes tempted to cook observations for an experiment. This practice requires considerable ingenuity, but should be avoided since it may lead to conclusions which are incorrect. In a computer-aided experimentation package a set of random numbers will be generated which are very close to the recorded values and the program will guide students to determine the possible reasons for discrepancies between the theoretical and experimental results. This can develop an element of confidence in the reliability of the recorded values and encourage the sense of curiosity in students. It is essential to note that, no experimentation performed on a computer can provide the experience gained in a real laboratory, in terms of developing practical skills in using the measuring equipment or assembling a system. A computer-aided experimentation package should certainly help in understanding, analysing and writing technical reports.

It is necessary to emphasize that, there is no way for a computer to replace a real laboratory session and there is no way for a computer to simulate the environment to develop physical skill and confidence which a person can gain by working in a real laboratory. However, the use of computers can assist students and increase the efficiency and effectiveness of the practical training.

8. THE HEATO PACKAGE

In order to measure the reliability of the claims made in section 5, the computer-aided experimentation package HEATO has been developed. The package analyses the heat transfer between the air flowing in a pipe and the wall of uniform temperature. The program provides users with comprehensive information on the details of the theory, apparatus and procedure as well as guidance on formal analysis and presentation of the results. The program HEATO can be used either with a set of recorded experimental data or by a set of normally distributed pseudo random numbers determined from the mean and standard deviation values obtained from the results of experiments conducted over the past 15 years. The graphical output and different curve fitting capabilities of the package removes the inauthentic labour of the report preparation. Also the full accessibility of the theoretical results based on two different models provides students with an environment in which the experimental and theoretical results can be compared. A selected output of the package for a set of randomly generated data is given in the Appendix. The program HEATO has been written in ForTran77 and Graphics Kernel System GKS library has been used for graphical outputs. The program runs on a basic microcomputer running the DOS operating system with 640K memory and an EGA or VGA graphics card.

9. CONCLUSIONS

It has been shown that experimentation is an important part of the engineering education and any effort in reducing its credibility can create a large vacuum in the process of enhancing scientific knowledge. It has also been shown that the computer-aided experimentation environment can be a valuable tool for performing experiments in certain circumstances. Although, at present there are insufficient data to substantiate the full benefit of using computer-aided experimentation packages, the initial observations on a limited number of students have been promising.

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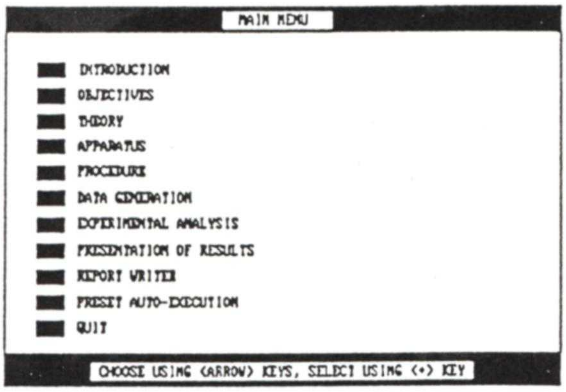
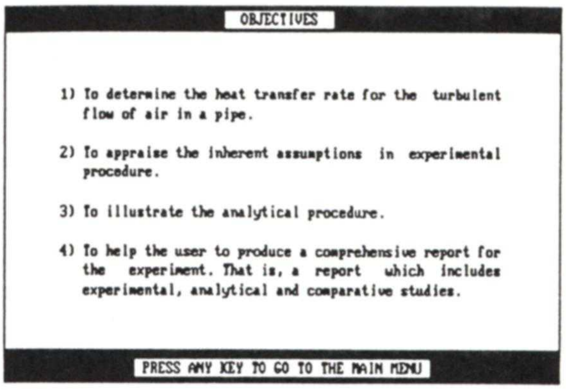
APPENDIX



Main menu frame



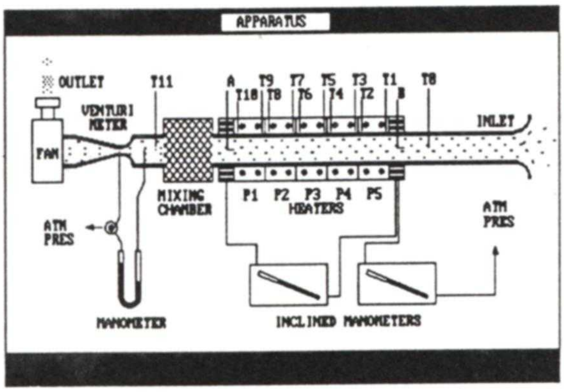
1) To determine the heat transfer rate for the turbulent flow of air in a pipe.

2) To appraise the inherent assumptions in experimental procedure.

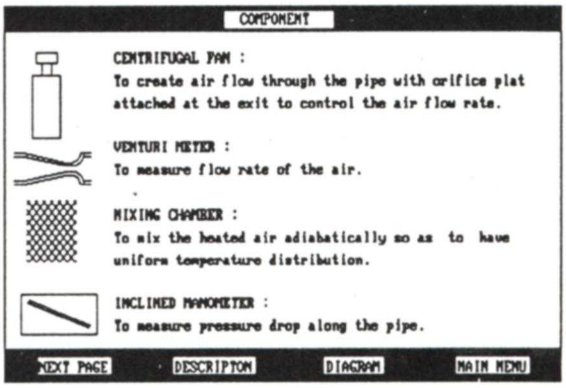
3) To illustrate the analytical procedure.

4) To help the user to produce a comprehensive report for the experiment. That is, a report which includes experimental, analytical and comparative studies.

Objectives frame



Apparatus



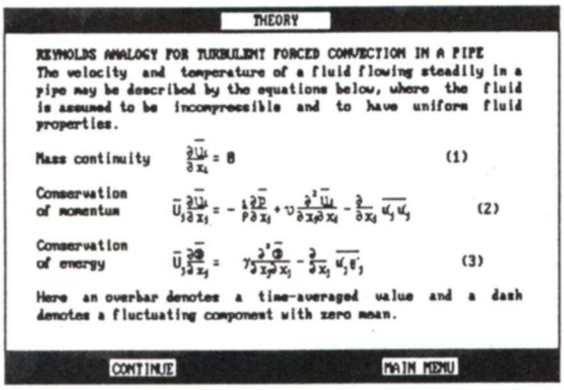
CENTRIFUGAL FAN :
To create air flow through the pipe with orifice plat attached at the exit to control the air flow rate.

VENTURI METER :
To measure flow rate of the air.

MIXING CHAMBER :
To mix the heated air adiabatically so as to have uniform temperature distribution.

INCLINED MANOMETER :
To measure pressure drop along the pipe.

Components Page(1)



REYNOLDS ANALOGY FOR TURBULENT FORCED CONVECTION IN A PIPE
The velocity and temperature of a fluid flowing steadily in a pipe may be described by the equations below, where the fluid is assumed to be incompressible and to have uniform fluid properties.

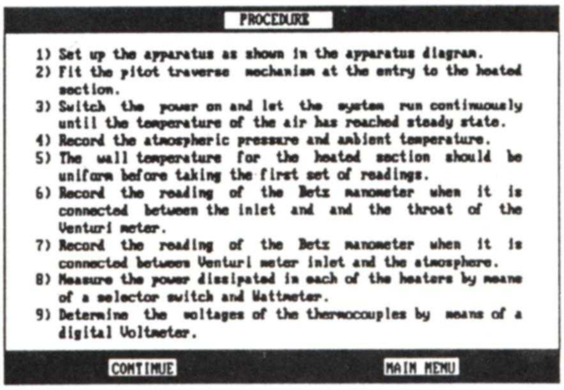
Mass continuity $\frac{\partial \bar{U}_i}{\partial x_i} = 0$ (1)

Conservation of momentum $\bar{U}_j \frac{\partial \bar{U}_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \bar{P}}{\partial x_i} + \nu \frac{\partial^2 \bar{U}_i}{\partial x_j \partial x_j} - \frac{\partial}{\partial x_j}\overline{u_i' u_j'}$ (2)

Conservation of energy $\bar{U}_j \frac{\partial \bar{\Theta}}{\partial x_j} = \gamma \frac{\partial^2 \bar{\Theta}}{\partial x_j \partial x_j} - \frac{\partial}{\partial x_j}\overline{u_j' \theta_j'}$ (3)

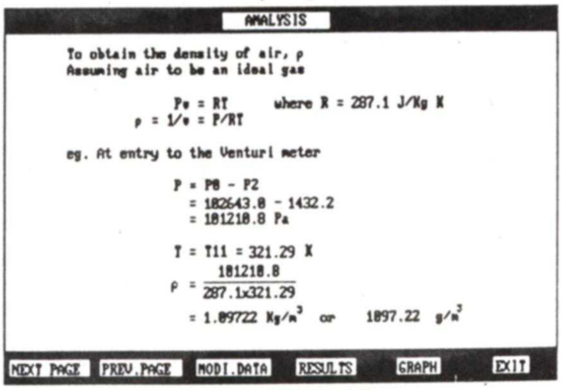
Here an overbar denotes a time-averaged value and a dash denotes a fluctuating component with zero mean.

Theory Page(1)



1) Set up the apparatus as shown in the apparatus diagram.
2) Fit the pitot traverse mechanism at the entry to the heated section.
3) Switch the power on and let the system run continuously until the temperature of the air has reached steady state.
4) Record the atmospheric pressure and ambient temperature.
5) The wall temperature for the heated section should be uniform before taking the first set of readings.
6) Record the reading of the Betz manometer when it is connected between the inlet and and the throat of the Venturi meter.
7) Record the reading of the Betz manometer when it is connected between Venturi meter inlet and the atmosphere.
8) Measure the power dissipated in each of the heaters by means of a selector switch and Wattmeter.
9) Determine the voltages of the thermocouples by means of a digital Voltmeter.

Procedure Page(1)



To obtain the density of air, ρ
Assuming air to be an ideal gas

$Pv = RT$ where $R = 287.1$ J/Kg K
$\rho = 1/v = P/RT$

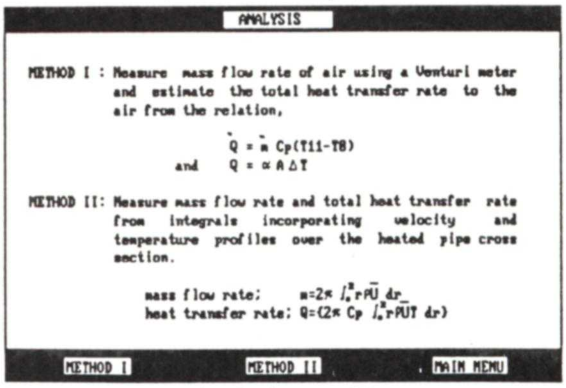
eg. At entry to the Venturi meter

$P = P0 - P2$
$= 102643.0 - 1432.2$
$= 101210.8$ Pa

$T = T11 = 321.29$ K

$\rho = \frac{101210.8}{287.1 \times 321.29}$
$= 1.09722$ Kg/m^3 or 1097.22 g/m^3

Analysis page(1)



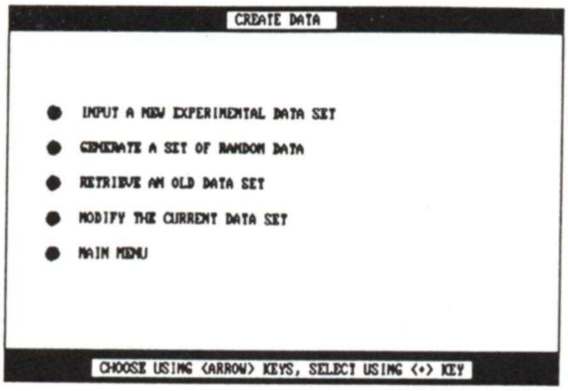
METHOD I : Measure mass flow rate of air using a Venturi meter and estimate the total heat transfer rate to the air from the relation,

$\dot{Q} = \dot{m}\, Cp(T11-T0)$
and $Q = \alpha A \Delta T$

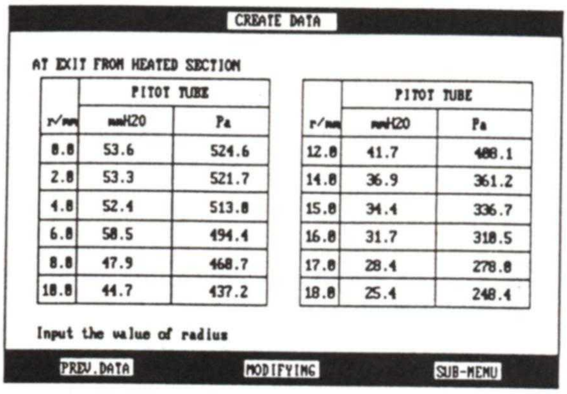
METHOD II: Measure mass flow rate and total heat transfer rate from integrals incorporating velocity and temperature profiles over the heated pipe cross section.

mass flow rate; $m = 2\pi \int_0^R r \rho \bar{U}\, dr$
heat transfer rate; $Q = (2\pi\, Cp \int_0^R r \rho \bar{U} \bar{T}\, dr)$

Analysis page(2)



Input data page(1)



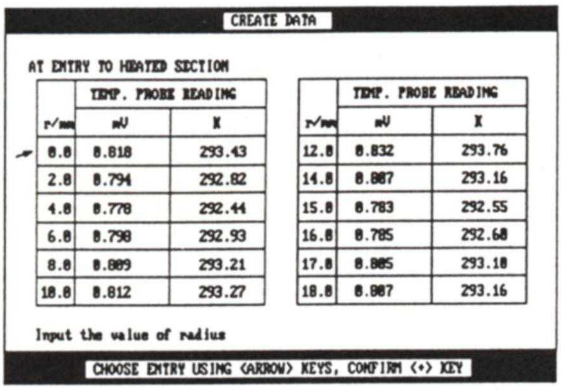
AT EXIT FROM HEATED SECTION

	PITOT TUBE	
r/mm	mmH2O	Pa
0.0	53.6	524.6
2.0	53.3	521.7
4.0	52.4	513.0
6.0	50.5	494.4
8.0	47.9	468.7
10.0	44.7	437.2

	PITOT TUBE	
r/mm	mmH2O	Pa
12.0	41.7	408.1
14.0	36.9	361.2
15.0	34.4	336.7
16.0	31.7	310.5
17.0	28.4	278.0
18.0	25.4	248.4

Input the value of radius

Input data page(4)



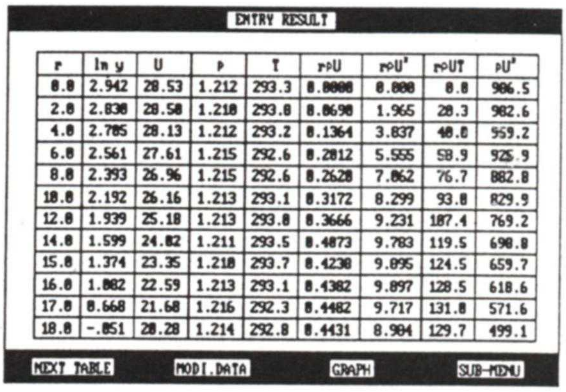
AT ENTRY TO HEATED SECTION

	TEMP. PROBE READING	
r/mm	mV	K
0.0	0.818	293.43
2.0	0.794	292.82
4.0	0.778	292.44
6.0	0.798	292.93
8.0	0.809	293.21
10.0	0.812	293.27

	TEMP. PROBE READING	
r/mm	mV	K
12.0	0.832	293.76
14.0	0.807	293.16
15.0	0.783	292.55
16.0	0.785	292.60
17.0	0.805	293.10
18.0	0.807	293.16

Input the value of radius

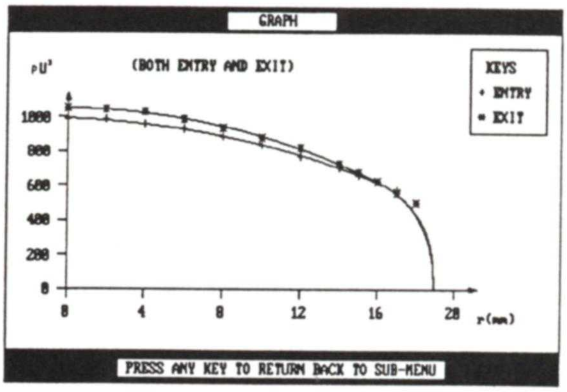
Input data page(6)



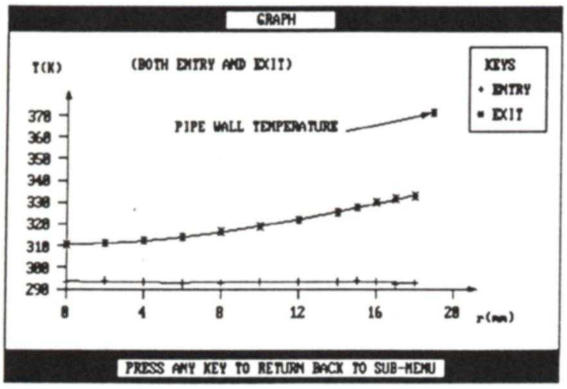
r	ln y	U	ρ	T	rρU	rρU²	rρUT	ρU²
0.0	2.942	28.53	1.212	293.3	0.0000	0.000	0.0	986.5
2.0	2.830	28.50	1.210	293.0	0.0690	1.965	20.3	982.6
4.0	2.785	28.13	1.212	293.2	0.1364	3.837	40.0	959.2
6.0	2.561	27.61	1.215	292.6	0.2012	5.555	58.9	925.9
8.0	2.393	26.96	1.215	292.6	0.2620	7.062	76.7	882.8
10.0	2.192	26.16	1.213	293.1	0.3172	8.299	93.0	829.9
12.0	1.939	25.18	1.213	293.0	0.3666	9.231	107.4	769.2
14.0	1.599	24.02	1.211	293.5	0.4073	9.783	119.5	698.8
15.0	1.374	23.35	1.210	293.7	0.4238	9.895	124.5	659.7
16.0	1.082	22.59	1.213	293.1	0.4382	9.897	128.5	618.6
17.0	0.668	21.68	1.216	292.3	0.4482	9.717	131.0	571.6
18.0	-.051	20.28	1.214	292.8	0.4431	8.984	129.7	499.1

Result page(1)

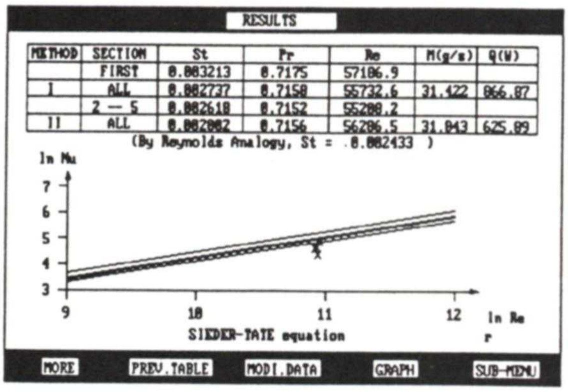
Graph page(4)



Graph page(5)



Result page(2)



METHOD	SECTION	St	Pr	Re	M(g/s)	Q(W)
	FIRST	0.003213	0.7175	57106.9		
I	ALL	0.002737	0.7150	55732.6	31.422	866.07
	2 — 5	0.002610	0.7152	55200.2		
II	ALL	0.002002	0.7156	56206.5	31.043	625.09

(By Reynolds Analogy, St = .0.002433)

Graph menu page(7)