EXPERIMENT PLANNING

The role of uncertainty analysis in experiment planning

DESIGN OF EXPERIMENTS

Experiment Design Factors

Experiment Design Protocol and Examples

DESIGN EXAMPLE

Forced-convection measurements for a new refrigerant

Before initiating an experiment, experimentalists ought to ask!

1) What am I looking for?
2) Why am I measuring this?
3) Does the measurement really answer any of my questions?
4) What does the measurement tell me?

Some less elementary questions needed to be answered before an experiment:

1. What primary variables shall be investigated?
2. What control must be exerted on the experiment?
3. What ranges of the primary variables will be necessary to describe the phenomena under study?
4. How many data points should be taken in the various ranges of operation to ensure good sampling of data considering instrument accuracy and other factors?
5. What instrument accuracy is required for each measurement?
6. If a dynamic measurement is involved, what frequency response must the instrument have?
7. Are the instruments available commercially, or must they be constructed especially for the particular experiment?
8. What safety precautions are necessary if some kind of hazardous operation is involved in the experiment?
9. What financial resources are available to perform the experiment, and how do the various instrument requirements fit into the proposed budget?
10. What provisions have been made for recording the data?
11. What provisions have been made for either on-line or subsequent computer reduction of data?

What primary variables shall be investigated?

Pressure, temperature, velocity, force, etc.

↓

Absolute Performance Test

What control must be exerted on the experiment?

Heat Loss → room temperature control

The effect of smoke on eating habits of mice→smoke must be controlled

↓

Relative Performance Test

Data recording Devices

a) automatic recording (plotter, pc via das, etc.)
b) notebook+pen, sketching

GENERALIZED EXPERIMENTAL PROCEDURE

1.a Establish the need for the experiment→Does it already exist in the literature?

1.b Establish the optimum budgetary, manpower, and time requirements, including time sequencing of the project. Modify scope of the experiment to actual budget, manpower and time schedule which are allowable.

2. Begin detail planning for the experiment; clearly establish objectives of experiment (verify performance of production model, verify theoretical analysis of particular physical phenomenon, etc.). If experiments are similar to those of previous investigators, be sure to make use of experience of the previous workers. Never overlook the possibility that the work may have been done before and reported in the literature.

3. Continue planning by performing the following steps.

3.a Establish the primary variables which must be measured (force, strain, flow, pressure, temperature, etc.)

3.b Determine as nearly as possible the accuracy which may be required in the primary measurements and the number of such measurements which will be required for proper data analysis.

3.c Set up data reduction calculations before conducting the experiments to be sure that adequate data are being collected to meet the objectives of the experiment.

3.d Analyze the possible errors in the anticipated results before the experiments are conducted so that modifications in the accuracy requirements on the various measurements may be changed if necessary.

4. Select instrumentation for the various measurements to match the anticipated accuracy requirements. Modify the instrumentation to match budgetary limitations if necessary.

5. Collect a few data points and conduct a preliminary analysis of these data to be sure that the experiment is going as planned.

6. Modify the experimental apparatus and/or procedure in accordance with the findings in item 5.

7. Collect the bulk of experimental data and analyze the results.

8. Organize, discuss, and publish the findings and results of the experiments, being sure to include information pertaining to all items 1 to 7, above.

The role of uncertainty analysis in experiment planning

In an experimental campaign the objective is to obtain values of variables which will eventually lead us to a conclusion about a specific physical phenomenon.

There may be several ways to measure these variables. An electric-power (Joule heating) measurement could be performed e.g., by measuring current and voltage and taking the product of these variables. The power may also be calculated by measuring the voltage drop across a known resistor. Or, the heat dissipated from the power generating device may be determined by measuring the calorific change in the surrounding medium. The choice of the method used can be made on the basis of an uncertainty analysis, which indicates the relative uncertainty of each method.

A flow measurement might be performed by sensing the pressure drop across an orifice (obstructionmeter) or by counting the number of revolutions of a turbine placed in the flow. In the first case, the uncertainty depends on the accuracy of a measurement of pressure differential and other variables, such as flow area, while in the second case the overall uncertainty depends on the accuracy of counting and a time determination.

A careful uncertainty analysis during the experimental planning enables the experimenter to make a better selection of instruments for the program. The approximate steps to be followed during an uncertainty analysis are:

1. **Several alternative measurement techniques are selected once the variables to be measured have been established.**
2. **An uncertainty analysis is performed on each measurement technique, taking into account the estimated accuracies of the instrument that will actually be used.**
3. **The different measurement techniques are then compared on the basis of cost, availability of instrumentation, ease of data collection and calculated uncertainty. The technique with the least uncertainty is clearly the most desirable one, but it may still be too expensive.**

DESIGN OF EXPERIMENTS

Experiments can coarsely be classified in two categories: experiments that serve *absolute performance analysis* or experiments that serve comparison to other experiments within the same field (*relative performance analysis*).

Classification of experiments may also be done regarding a more detailed description such that it serves to create an overall protocol for execution of experiment design

Type of experiment	**1.Fundemental Research, Company Proprietary, or Government Classified**	**2.Fundemental Research, Open Results**	**3. Developmental Research, Company Proprietary**	**4. Developmental Research, Open Results**
Type of output publication or reports	Internal reports, with portions possibly for journals	Conference papers, journal articles	Internal reports, some highly restricted	Open results unlikely legally protected
Presentation Requirements, special meetings, etc.	Internal and external	Professional society meetings	Internal restricted	Internal
Outcome known or anticipated	No	No	Sometimes	Sometimes
Uncertainty analysis	Yes	Yes	Yes	Yes
Personnel require special background	Yes	Yes	Possibly not	Possibly not
Significant involvement of other groups of people	Not necessarily	Not necessarily	Yes, management, finance, legal	Yes, management, finance, legal
Novel experimental design required	Variable, mostly no	Variable, mostly no	Probably yes	Probably yes
Special instruments required or off-the-shelf	Usually off-the-shelf	Usually off-the-shelf	Some special may be developed	Some special may be developed
Expense limits, budget restraints	Usually modest	Modest	Highly variable	Highly variable
Time constraints	Usually relaxed	Relaxed	Usually rushed	Usually rushed
Safety requirements	Yes	Yes	Yes	Yes
Example of this type of periment	Study of laser or infrared transmission of exotic materials Studies of genetic engineering and cloning	Study of boiling of fluorocarbons Study of combustion products for engines	Semiconductor chip growth/manufacturing methods Laser cutting methods in manufacturing	Semiconductor chip growth/manufacturing methods Laser cutting methods in manufacturing

Not as easy as it seems!

A. Type of experiment	**5.Testing According to Code or Specified Standards**	**6. Testing According to Accepted method, but not Code**	**7. Testing for Commercial Promotion Purposes**	**8. Just want to know**
B. Type of output publication or reports	Internal report or report to regulatory agency	Internal report	Product literature, advertising material	Informal report
C. Presentation Requirements, special meetings, etc.	Minimal	Internal	Special audiovisual presentations	Verbal to supervisor
D. Outcome known or anticipated	Yes Yes	Sometimes Yes	Usually Surprises not anticipated	Possibly Possibly
E. Uncertainty analysis	No	Yes	Probably not	Minimal
F. Personnel require special background	Usually trained for tests	Usually not	Usually not	No
G. Significant involvement of other groups of people	Usually not	Probably not	Publications and promotional persons	No
H. Novel experimental design required	No	No	No	No
I. Special instruments required or off-the-shelf	Off-the-shelf	Off-the-shelf	Off-the-shelf but may need special effects	Off-the-shelf but may need special effects
J. Expense limits, budget restraints	Usually well-defined	Usually well-defined	Controlled	Low budget
K. Time constraints	Variable	Usually well-defined	Usually well-defined	Short time
L. Safety requirements	Yes	Yes	Yes	Yes
T. Example of this type of experiment	Calorific value of foods by ASTM (American Society for Testing of Materials) tests Viscosity index of oils by ASTM test	Forced convection in a tube Sound absorption in solid materials	Video demonstration/test of strength of paper towels Comfort test of auto seating	Anything e.g., How long does it take to boil a cup of water in a microwave?

Hazardous material is not only considered within the framework of safety requirements but also regulations Concerning the disposal of such material must be taken into account.

Type 1 and 2 experiments involving basic research are very specialized and require execution by people expert in the field. The design of such experiments are therefore a procedure that is highly variable.

Type 3 and 4 experiments involve developmental work and may frequently be assigned to the average engineering professional. The design protocol that is going to be formed here is applicable to such projects.

Type 5 experiments that require testing according to "code" require very little "design" but may involve a significant amount of coordination to ensure that the results match the code requirements.

The protocol is assumed to be applicable to Type 6 to 8 experiments as well.

In preparing to conduct or design an experiment one may view the process as an activity that is working backward from the reporting requirements indicated in row B of Table 2.

Usually the output requirements set the boundary conditions for the design and execution phases of an experimental campaign. In the case of a fundamental research project, the client may be the scholarly journal in the field. However in some other cases, the project is funded by companies and their expectations need to be respected. For a development project, the output may be a legal patent or a process that is maintained as a trade secret. The handling of the results for such projects are obviously different from those results that will be published in the open literature.

Experiment Design Factors

We should now consider the factors that will enter into the experiment design process. The factors are summarized in Table 3. The source of item description in column B indicates the person(s), literature information, or other item in the table that will be used by the experiment designer to obtain the specified information.

Item number	Item Description	Source of item description
1	Overall objectives	Management or client/customer
2	List of specific results needed including range(s) of variables, accuracy, and uncertainties desired	Coordinated between management and experimental personnel
3	Sample presentation format for results	Coordinated between management and experimental personnel
4	Method/Technique for overall experiment	Code specification for standard test, various literature for established techniques, novel experiment design in other cases
5	Parameters needed to calculate/determine results	Experimental personnel and literature
6	Measured quantities needed to calculate above parameters	Item 5
7	Ranges expected for measured quantities	Items 2 and 5
8	Method/technique(s) for individual measurements	Items 6 and 7
9	Anticipated uncertainties in individual measurements	Manufacturers literature, information in other sources
10	Apparatus preliminary design	Results of above determinations
11	Sample calculations based on apparatus design	Above factors
12	Calculations needed to check consistency of measurements; energy, mass, force balances, etc.	Items 4, 5 and 6
13	Decision on measurement, methods for individual parameters	All information above
14	Estimate for uncertainties of final results	Calculation methods
15	Modifications to apparatus design and measurement techniques based on one or more of the above factors	Above items

Experiment Design Protocol and Examples

A. **1. Determine the type or category of experiment by consulting Table 2. Consider overlapping categories.**

B. 2. Examine each of characteristic entries in Table 2. pertaining to the experiment type selected. Write down preliminary checklist of Things to Do based on this examination.

C. 3. Begin working through the sequence of tasks in Table 2. Write down known information for as many items as possible. Prepare a list of needed activities in accordance with the known information and items yet to be determined.

D. 4. To the extent possible, prepare a written schedule for accomplishing the tasks in Table 3.

E. 5. Refine the design by working through all the tasks in Table 3 in detail.

The experiment design protocol may seem to be oversimplified and way too compact however it has to be kept in mind that the above protocol is a compressed version of Table 2 and 3.

DESIGN EXAMPLE

Forced-convection measurements for a new refrigerant

The manufacturer of a new refrigerant system desires to determine the heat transfer performance of their product in terms of the conventional parameters. They contract with an independent testing laboratory to perform the measurements. After consulting the laboratory personnel and the manufacturer, the preliminary specifications for the test are established as:

Fluid properties for saturated liquid conditions from 0°C to 40°C
Density ≈ 1200 kg/m^3
Dynamic viscosity ≈ 3x10^{-4} kg/ms
Thermal conductivity ≈ 0.075 W/m°C
Specific heat ≈ 1.4 kJ/kg°C
Prandtl number=5.6
Desired range of Reynolds number: 20000 to 150000
Fluid temperature range: same as given above
Flow geometry, smooth circular tube:
Tube diameters: 2.0 t0 35 mm
Tube lengths: sufficient for developed flow
Temperature differences between tube and fluid: 5 to 15 °C
Heat fluxes: As determined in experiment design
Flow rates: As determined in experiment design

Desired uncertainty in determination of heat transfer coefficients: how good can you get?

Anticipated results: Correlate with conventional forced-convection relations available in standard-heat transfer literature and handbooks. No surprises are anticipated, and management will view with some alarm significant deviations from these unexpected results.

The experimental team is asked to come up with a suitable plan for design of the experiment that will be acceptable to the manufacturer/client in terms of meeting the above preliminary specifications. Based on the design and/or proposed modifications, a proposal will be presented to the client for the execution of the experiment along with appropriate cost and time schedules.

Design Protocol

The type of experiment is #6

A. Type of experiment	6. Testing According to Accepted method, but not Code
B. Type of output publication or reports	Internal report
C. Presentation Requirements, special meetings, etc.	Internal
D. Outcome known or anticipated	Sometimes Yes
E. Uncertainty analysis	Yes
F. Personnel require special background	Usually not
G. Significant involvement of other groups of people	Probably not
H. Novel experimental design required	No
I. Special instruments required or off-the-shelf	Off-the-shelf
J. Expense limits, budget restraints	Usually well-defined
K. Time constraints	Usually well-defined
L. Safety requirements	Yes
T. Example of this type of experiment	Forced convection in a tube Sound absorption in solid materials

Same comments as in table

D: anticipated from the appropriate relation in the next slide

J, K: will be proposed to the manufacturer when the technical design is established.

L: standard safety measures will apply

Physical Situation	Type of Fluid	Range of Validity	Heat-Transfer Relation	Fluid Properties Evaluated At
Forced convection over flat plate, plate heated over entire length	Gas or liquid	Laminar: $Re_x < 5 \times 10^5$	$Nu_x = 0.332\, Re_x^{1/2} Pr^{1/3}$	Film temperature T_f
		Turbulent: $Re_x > 5 \times 10^5$	$St_x\, Pr^{2/3} = 0.0296\, Re_x^{-1/5}$	
		Laminar: $Re_L < 5 \times 10^5$	$\overline{Nu_L} = 0.664\, Re_L^{1/2} Pr^{1/3}$	
		Turbulent: $Re_L > 5 \times 10^5$	$\overline{Nu_L} = .0.037\, Re_L^{0.8} - 871/Pr^{1/3}$	
Forced convection in smooth circular tube	Gas or liquid	$Re_d > 3000$	$\overline{Nu_d} = 0.023\, Re_d^{0.8} Pr^n$; $n = 0.4$ for heating; $n = 0.3$ for cooling	Average bulk temperature of fluid
		$Re_d < 2100$ and $Re_d Pr\left(\frac{d}{L}\right) > 10$	$\overline{Nu_d} = 1.86. Re_d\, Pr/^{1/3} \left(\frac{d}{L}\right)^{1/3} \left(\frac{\mu}{\mu_w}\right)^{0.14}$	
Forced-convection crossflow over cylinder	Gas or liquid	$40 < Re_d < 4000$	$\overline{Nu_d} = 0.683\, Re_d^{0.466} Pr^{1/3}$	Film temperature T_f
		$4000 < Re_d < 40{,}000$	$\overline{Nu_d} = 0.193\, Re_d^{0.618} Pr^{1/3}$	Film temperature T_f
		$40{,}000 < Re_d < 400{,}000$	$\overline{Nu_d} = 0.0266\, Re_d^{0.805} Pr^{1/3}$	
Forced convection over spheres	Gas	$17 < Re_d < 70{,}000$	$\overline{Nu_d} = 0.37\, Re_d^{0.6}$	Film temperature T_f
	Liquid	$1 < Re_d < 200{,}000$	$\overline{Nu_d}\, Pr^{-0.3} \left(\frac{\mu}{\mu_w}\right)^{0.25} = 1.2 + 0.5\, Re_d^{0.54}$	Free-stream temperature T_∞
Free convection from vertical flat plate	Gas or liquid	$10^4 < Gr_L Pr < 10^9$	$\overline{Nu_L} = 0.59. Gr_L Pr/^{1/4}$	Film temperature T_f
		$10^9 < Gr_L Pr < 10^{12}$	$\overline{Nu_L} = 0.10. Gr_L Pr/^{1/3}$	Film temperature T_f
Free convection from horizontal cylinders	Gas or liquid	$10^4 < Gr_d Pr < 10^9$	$\overline{Nu_d} = 0.53. Gr_d Pr/^{1/4}$	Film temperature T_f
		$10^9 < Gr_d Pr < 10^{12}$	$\overline{Nu_d} = 0.13. Gr_d Pr/^{1/3}$	Film temperature T_f

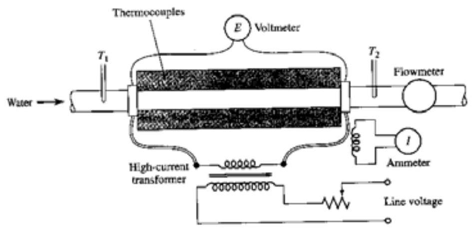
Definition of symbols: All quantities in consistent set of units so that Nu, Re, Pr, Gr, and St are dimensionless.

$\overline{Nu_d} = \frac{\bar{h}d}{k}$ $\overline{Nu_L} = \frac{\bar{h}L}{k}$ $Nu_x = \frac{h_x x}{k}$ $Re_d = \frac{\rho u_\infty d}{\mu}$ for flow over cylinders or spheres $Re_d = \frac{\rho u_m d}{\mu}$ for flow in tubes $Re_x = \frac{\rho u_\infty x}{\mu}$

$Re_L = \frac{\rho u_\infty L}{\mu}$ $Pr = \frac{c_p \mu}{k}$ $Gr_L = \frac{\rho^2 g \beta. T_w - T_x/L^3}{\mu^2}$ $Gr_d = \frac{\rho^2 g \beta. T_w - T_\infty/d^3}{\mu^2}$ $St_x = \frac{h_x}{\rho u_\infty c_p}$

Frequently use convection-heat transfer correlations

Preliminary Calculations



Schematic of apparatus for determination of forced-convection heat transfer coefficients in smooth tubes

$$q = \dot{m}C_p \Delta T_{fluid} = hA\left(T_w - \overline{T}_{fluid}\right) = EI$$

$$q = \dot{m}C_p\left(T_2 - T_1\right)$$

Estimate of Range of Values for Heat-Transfer Coefficients

$$Nu = 0.023 Re^{0.8} Pr^{0.4} = \frac{hd}{k}$$

With the property values specified by the manufacturer,

Re=20000, d=35 mm → **h=271 W/m²°C**

Re=20000, d=2 mm → **h=4740 W/m²°C**

Re=150000, d=35 mm → **h=1360 W/m²°C**

Re=150000, d=2 mm → **h=23760 W/m²°C**

Estimate of Flow Rate Ranges

$$\dot{m} = \rho u_m A_c : \quad \dot{m} = Re\,\mu \frac{\pi d}{4}$$

Re=20000, d=2 mm → **0.00942** kg/s

Re=20000, d=35 mm → **0.16485 kg/s**

Re=150000, d=2 mm → **0.07065 kg/s**

Re=150000, d=35 mm → **1.23637 kg/s**

The range of flow rates is very broad, ranging from **0.00942** to **1.23637** kg/s. This suggests that multiple experimental setups may be required to cover the range, at excessive cost to the manufacturer.

Heat-Transfer Rates

For the maximum suggested temperature difference of 15 °C, we now examine the heat transfer rates for a tube length (L) of 2 meters:

$$q = hA(T_w - T_{fluid})$$

, where

Re=20000, d=2 mm → q=**893 W**

Re=20000, d=35 mm → q=**894 W**

Re=150000, d=2 mm → q=**4477 W**

Re=150000, d=35 mm → q=**4477 W**

Change in Fluid Temperature

The fluid temperature rise may be computed from

$$q = \dot{m} C_p \Delta T_{fluid}$$

Re=20000, d=2 mm → ΔT_{fluid} = 67.71°C

Re=20000, d=35 mm → ΔT_{fluid} = 3.87°C

Re=150000, d=2 mm → ΔT_{fluid} = 45.26°C

Re=150000, d=35 mm → ΔT_{fluid} = 2.59°C

Suggested Modifications to Design Parameters

- broad range of flow rates
- results are expected to follow an anticipated correlation regardless of the tube diameter

⇩

Single tube of 12 mm diameter

T_1=0°C

T_w-T_{fluid}=15°C

Re	**20000**	**150000**
$\dot{m}$	0.0566 kg/s	0.424 kg/s
h	790 W/m²°C	3961 W/m²°C
q	894 W	4477 W
T_2-T_1	11.13°C	7.55°C

Above list shows that the flow rates are now within a factor of 10 which may be accommodated with a single flow measuring device.

Primary Measurements Summary

•Primary measurements to be performed
•Their range of values
•Estimate of uncertainties

will be presented.

Calculation Checks to Determine Satisfactory Experiment Operation

$$q = \dot{m}C_p(T_2 - T_1) = P = EI \qquad \text{(Assuming no heat loss)}$$

The heat transfer rate q is determined by two methods; electric power and flow energy balance.

Proposed measurement method, associated ranges and uncertainty

Variables	Method of Measurement	Range	Estimated Uncertainty
T_1, T_2	Type E thermocouple(tc)	0-40°C	±0.5 °C
T_2-T_1	Type E tc. thermopile	0-15°C	±0.3 °C
T_w	Type E thermocouple	0-60°C	±0.5 °C
m	turbine meter	0.05-0.5 kg/s	±0.5%
E	Voltmeter	2-20 volts	±0.3%
I	Ammeter	100-400 amps	±0.3%

For **Re=20000**, the product function uncertainty is:

Flow Energy

$$\frac{W_q}{q} = \left[(0.005)^2 + \left(\frac{0.3}{11.13}\right)^2\right]^{1/2} = 0.027$$

Electric Power

$$\frac{W_p}{P} = \left[(0.003)^2 + (0.003)^2\right]^{1/2} = 0.0042$$

For **Re=150000**, the product function uncertainty is:

$$\frac{W_q}{q} = \left[(0.005)^2 + \left(\frac{0.3}{11.13}\right)^2\right]^{1/2} = 0.040$$

$$\frac{W_p}{P} = \left[(0.003)^2 + (0.003)^2\right]^{1/2} = 0.0042$$

The above calculations indicate that the energy balance might be expected to check within 4%. The calculation also shows that the electric power measurement is clearly preferred for calculating the heat transfer coefficient.

$$q = EI = hA(T_{wall} - T_{fluid})$$

Heating Device Design Calculations

The heating mechanism proposed is an electrically heated tube. We select a stainless-steel tube with dimensions

Inside diameter = d_i = 12 mm
Wall thickness = 0.8 mm
Length = L = 2 m.

The resistivity of stainless-steel is approximately ρ = 70 μΩ.cm, so the tube resistance is:

$$R = \frac{\rho L}{A} = \frac{(70\times10^{-6})(200)(4)}{\pi(1.36^2 - 1.2^2)} = 0.0435\Omega$$

The electrical power is **P=I²R**, so, for the design range of power from 894 to 4480 W we have

P	894	4480	W	
I	143	321	A	$(I = \sqrt{P/R})$
E	6.22	14	V	$(E = RI)$

These electrical parameters can be accommodated by an off-the-shelf variac or transformer

Estimate of Uncertainty in Determination of h

Although the previous calculation of the uncertainty on electrical power indicated 0.4%, let us assume a safer 1% uncertainty value to be used in the calculation of the uncertainty on h.

$$h = \frac{q}{A(T_w - T_{fluid})} = \frac{q}{A\Delta T}$$

where we set $\Delta T = T_w - T_{fluid}$. We take two conditions: ΔT=5°C and 15°C along with $W_T = \pm 0.5$°C.

$$W_{\Delta T} = \left[(0.5)^2 + (0.5)^2\right]^{1/2} = 0.71^\circ C$$

$$W_h = \left[\left(\frac{W_q}{q}\right)^2 + \left(\frac{W_{\Delta T}}{\Delta T}\right)^2\right]^{1/2}$$

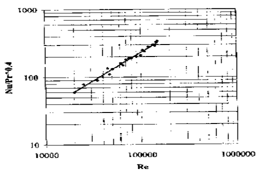
At ΔT=5°C
$$\frac{W_h}{h} = \left[(0.01)^2 + \left(\frac{0.71}{5}\right)^2\right]^{1/2} = 0.142 = 14.2\%$$

At ΔT=15°C
$$\frac{W_h}{h} = \left[(0.01)^2 + \left(\frac{0.71}{15}\right)^2\right]^{1/2} = 0.0483 = 4.83\%$$

Thus, small temperature differences between the tube and the fluid should be avoided.

Expected Results

The expected results will take the form illustrated below; in Fig. 2.
The plot should include a correlation trend line and correlation coefficient r^2.



Data Collection and Calculation of Results

A. General observations and records
1. Ambient temperature and pressure
2. Material of construction and electrical properties of heated test section
3. Calibration information for instruments
4. Observations of unsteady operation or unusual behavior

B. Primary measurements
1. Inlet and exit fluid bulk temperatures for test section T_1 and T_2
2. Tube wall temperatures T_w, at least eight
3. Voltage impressed on test section E, volts
4. Current through test section I, amperes
5. Flowmeter readout × factor to convert to mass flow rate m in kg/s
6. Direct measurement of fluid $\Delta T = T_2 - T_1$
7. Temperature at outside of insulation (check on effectiveness of insulation)
8. Pressure at inlet to test section
9. Dimensions of test section tube, inside and outside diameters d_i and d_o, and tube length L

C. Estimates of uncertainty in primary measurements at high and low limits of Reynolds number and high and low limits of temperature difference between tube wall and fluid. Estimate for quantities listed in **B**.

D. Calculated results
1. Flow rate = m = meter reading × factor to convert to kg/s
2. Flow cross-sectional area $A_c = \pi d_i^2/4$
3. Surface area for heat transfer $A = \pi d_i L$
4. Mean fluid temperature $Tm = (T_1 + T_2)/2$
5. Fluid viscosity, thermal conductivity, and Prandtl number evaluated at Tm
6. Mean wall temperature $Twm = \Sigma Tw/n$ for uniform spacing
7. Reynolds number $Re = (m/A_c)d_i/\mu$
8. Mean wall to fluid temperature difference $\Delta Tm = Twm - Tm$
9. Electric power input $P = EI$
10. Convection heat-transfer coefficient

$$h = P/A\Delta Tm, \ \mathrm{W/m^2 \cdot {}^\circ C}$$

11. Nusselt number = hd_i/k
12. Parameter $Nu/Pr^{0.4}$
13. Energy balance check for high and low values of Re:

$$P = EI = (?) = mc_p(T_2 - T_1) \text{ with } T_2 - T_1 \text{ values from direct measurement}$$

14. Check of electric resistance of tube:

$$R_{elec} = \frac{\rho_{elec} L}{A_{tube}} = \frac{4\rho_e L}{\pi\left(d_o^2 - d_i^2\right)} = (?) = \frac{E}{I}$$

E. Calculated uncertainties of results for high and low values of Reynolds number Re, and high and l wall to fluid temperature differences. Assume fluid properties and tube dimensions are exact.
1. Power: $w_P/P = [(w_E/E)^2 + (w_I/I)^2]^{1/2}$
2. Average wall to fluid temperature difference $\Delta Tm = Twm - Tm$

$$w_{\Delta Tm} = [(w_{Twm})^2 + (w_{Tm})^2]^{1/2}$$

Data Collection and Calculation of Results (contd)

3. Heat-transfer coefficient:

$$w_h/h = [(w_P/P)^2 + (w_{\Delta Tm}/\Delta Tm)^2]^{1/2}$$

4. Reynolds number: $w_{\mathrm{Re}}/\mathrm{Re} = w_m/m$
5. Nusselt number: $w_{\mathrm{Nu}}/\mathrm{Nu} = w_h/h$

F. Graphical presentation of results

1. Sample wall temperature profiles, T_w vs. x along tube length
2. $\mathrm{Nu}/\mathrm{Pr}^{0.4}$ vs. Re on loglog coordinates with trendline fit to data
3. Other correlation parameters if needed
4. Bounding lines on chart in No. 2 indicating calculated limits of uncertainties

Summary

The main reason why this experiment has been conducted is to back up expected heat transfer results with firm data. The method of publishing the results is left open. The manufacturer may decide that the results are only available for interested customers or may choose to seek publication in a technical platform.