UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Faculty of Engineering, Built Environment and Information Technology

Fakulteit Ingenieurswese, Bou-omgewing en Inligtingtegnologie

School of Engineering

Department of Mechanical and Aeeronautical Engineering

STUDY GUIDE:
HEAT TRANSFER
MTV410

Lecturers: Prof JP Meyer, Dr WG le Roux
Last Revision: 5 February 2020

Contents

ORGANISATIONAL COMPONENT

1. USING THE STUDY GUIDE

This study guide should not be seen simply as a document that is handed out on commencement of lectures at the beginning of a semester. It is in fact an extremely important document that you should use like a road map throughout the semester in order to complete this course successfully. Therefore, we shall spend the first lecture period on working through the study guide. This is to ensure that you are aware of the information contained in the document and to demonstrate to you how to put the document to optimal use.

The document consists of three parts. In the first part, introductory and organizational information is given, for example who the lecturer is, what to expect from the lecturer and what is expected from you. The second part contains very important study component information and the third part is the laboratory and experimental guides.

This study guide is a crucial part of the general study guide of the Department. In the study guide of the Department , information is given on the mission and vision of the department , general administration and regulations (professionalism and integrity, course related information and formal communication, workshop use and safety, grievances, support services, plagiarism, class representative duties, sick test and sick exam guidelines, vacation work, appeal process and adjustment of marks, university regulations, frequently asked questions), ECSA Graduate Attributes, ECSA knowledge areas, CDIO, new curriculum and assessment of cognitive levels. It is expected that you are very familiar with the content of the Departmental Study Guide. It is available in English and Afrikaans on the Department's website.

English:
https://www.up.ac.za/media/shared/120/Noticeboard/2020/departmental-studyguide-eng-2020_version21jan2020-002.zp185016.pdf

Afrikaans:
https://www.up.ac.za/media/shared/120/Noticeboard/2020/departementele-studiegids-afr-2020_weergawe21-jan2020-002.zp185015.pdf

Take note of the specific instructions in the above study guide on:

a. **Safety**
b. **Plagiarism**
c. **What to do if you were sick (very important)?**
d. **Appeal process on the adjustment of marks**

2. WHAT IS HEAT TRANSFER?

Heat transfer or thermal scienes (fluid mechanics and heat transfer) concerns the experimental fact that heat energy flows from bodies at a higher temperature to bodies at a lower temperature; in agreement with the Second Law of thermodynamics. It includes storage of heat as internal energy, the various mechanisms for heat transfer and the rate at which transfer takes place. The fundamental principle is the First Law of thermodynamics: the principle of energy conservation.

$$dU = \delta Q - \delta W$$

The change in internal energy (dU) equals heat gained (δQ) minus work done (δW). In heat transfer this principle is called the heat balance. We are not interested in the work term, δW, of the first law, only the heat term, δQ is relevant. With $\delta W = 0$ the first law becomes

$$dU = \delta Q$$

Thus, the change in internal energy = heat transferred.

Heat transfer is phenomenological, i.e. it is based on laws that are empirically observed, rather than deep theory.

Even-though heat transfer is presented very late in the mechanical engineering course, it is one of the basic subjects of the discipline. All mechanical and electrical systems dissipate heat. In most mechanical engineering systems, the conversion of heat in mechanical work is a fundamental principle of operation. Students wishing to train themselves as mechanical engineers must, accordingly, endeavour to obtain a comprehensive understanding of the principals involved in heat transfer. In addition, a wide knowledge of the application of the principles is required. MTV410 is only an introduction to the subject; after successful completion of the course the student should have a thorough understanding of the principles. The design of practical systems requires more than just comprehension of principles: an elegant design solution requires experience and consideration of many fine details. To design, requires that the designer integrates his knowledge of heat transfer, with his knowledge of thermodynamics, fluid flow and strength of materials, etc.

3. GENERAL PREMISE AND EDUCATIONAL APPROACH

The general objective with this module is to emphasize **understanding** rather than memorising, in order to **visualize** engineering solutions and to stimulate **creative thinking** in the field of heat transfer. A problem-driven approach to learning is followed. Student-centred and co-operative learning and teaching methods are applied during lectures and practical sessions, in order to develop the above-mentioned skills optimally, as well as to stimulate the development of communication skills, interpersonal skills and group dynamics.

Heat transfer is a critical component of not only mechanical engineering but also of various other disciplines. In the study of this module skills are developed that will enable the learner to understand and apply the basics and principles of heat transfer. These fundamentals will be used to solve a vast majority of engineering problems.

4. MODULE OBJECTIVES

- To develop a working knowledge of the differential equations of fluid motion.
- To establish the governing equations and a firm understanding of the applications of conduction, convection, and radiation heat transfer
- To develop a working knowledge of recognizing one-dimensional conduction heat transfer problems in a given application or real life problem
- To develop a thorough understanding of the steady state multidimensional heat transfer and their solution methodologies
- To develop a thorough understanding of the unsteady state heat transfer and their solution methodologies
- To develop adequate procedures for quantifying convection heat transfer effects in external and internal flow applications
- To develop the ability to use the heat transfer principles in thermal design problems

5. MODULE ASSESSMENT

Module objective	Intended educational outcomes	Means of assessment
Objective 1: To derive the differential equations of fluid flow	• Ability to derive the differential equations over a finite control volume of fluid flow for continuity, momentum, and energy. • Students will demonstrate the ability to apply these equations (with assumptions and simplifications) to solve simple problems	Locally developed tests and exams. Assignments
Objective 2: To establish the governing equations and a firm understanding of the applications of conduction, convection, and radiation heat transfer	• Students will demonstrate an understanding of the modes of heat transfers and solve problems using their associated rate equations. • Students will recognize multimode heat transfer problems and demonstrate the ability to use the energy balance conservation to solve such problems.	Locally developed tests and exams. Assignments Practical experiments and reports
Objective 3: To develop a working knowledge of recognizing one-dimensional conduction heat transfer problems in a given application or real life problem	• Students will demonstrate an ability to solve one-dimensional dimensional conduction including heat sources and convective boundary conditions, solving extended surface problems; straight pin fin; heat rate and temperature distribution.	Locally developed tests and exams. Assignments Practical experiments and reports
Objective 4: To develop a thorough understanding of the steady state multidimensional heat transfer and their solution methodologies	• Student will demonstrate an ability to establish a steady state, two-dimensional conduction problem. • Students will demonstrate an ability to solve two dimensional conduction problems using the method of shape factors, numerical and graphical methods.	Locally developed tests and exams. Assignments Practical experiments and reports
Objective 5: To develop a thorough understanding of the unsteady state heat transfer and their solution methodologies	• Students will demonstrate the ability to solve unsteady state, one-dimensional conduction using lumped capacitance method. • Students will demonstrate the ability to solve unsteady state, one-dimensional conduction graphically using Heisler charts.	Locally developed tests and exams. Assignments Practical experiments and reports Numerical modelling, boundary values and solutions.
Objective 6: To develop adequate procedures for quantifying convection heat transfer	• Ability to solve governing equations of convective heat transfer for internal flow with external convection; fully developed flow in a pipe velocity	Locally developed tests and exams. Assignments

effects in external and internal flow applications	effects, convection coefficient; transition effects; temperature dependent properties.	Practical experiments and reports
Objective 7: To develop the ability to use the heat transfer principles in thermal design problems	• Students will undertake the design of a thermal system to demonstrate the ability	Locally developed tests and exams. Assignments Practical experiments and reports Numerical modelling, boundary values and solutions.

6. LECTURER AND CONSULTING HOURS

	Name	Office	Tel:	E-mail:
Lecturer	Prof JP Meyer	Eng 3, 6-54	420 3104	josua.meyer@up.ac.za
Lecturer	Dr WG le Roux	Eng 3, 6-83	420 2446	willem.leroux@up.ac.za
Appointments for Prof Meyer	Ms Tersia Evans	Eng 3, 6-54	420 3104	tersia.evans@up.ac.za
Teaching assistants for practicals:				
Practical 1		Please refer all questions to the practical administrator		
Practical 2				
Practical 3				
Practical Administrator				

Please contact Ms Evans and schedule an appointment if you would like to consult Prof Meyer.

7. LECTURES ON YOUTUBE

All lectures (since 2013) are available on YouTube: https://www.youtube.com/HeatTransferUP
They area also available in three playlists:

2013 Playlist
https://www.youtube.com/playlist?list=PLogCfdsrpUTPlh-2jxa3IG3MxJmBJyayJ

2014 Playlist
https://www.youtube.com/playlist?list=PLogCfdsrpUTNodmUylEuhvirUtUELMjFF

2015 Playlist (Internal Forced Convection Chapter only as I was on sabbatical leave)
https://www.youtube.com/playlist?list=PLogCfdsrpUTPlh-2jxa3IG3MxJmBJyayJ

Problems on Internal Forced Convection only
https://www.youtube.com/playlist?list=PLogCfdsrpUTOGt9bQO6LftFoMh_7PNFIH

2016 Playlist: only on Transient conduction and internal forced convection
https://www.youtube.com/playlist?list=PLogCfdsrpUTOiRBa2HS8h2sdL1QXWuIFy

2017 Playlist
https://www.youtube.com/playlist?list=PLogCfdsrpUTMe1BLu_41xEsKG5rWQEeaV

2018 Playlist
https://www.youtube.com/playlist?list=PLogCfdsrpUTMCZyu5J7mPGLewFBNfJpjP

2019 Playlist
https://www.youtube.com/playlist?list=PLogCfdsrpUTNdT8k7dabj8UrEHYNHq8ne

The videos are not made available to provide an option between class attendance or not. It should be used as revision material and as supplementary information. The examples in the videos in most cases differ from year to year. Class attendance is very important and is encouraged.

The objectives of these videos are:

a. Additional opportunities for support/revision while preparing for tests and exams.

b. In many/most cases different problems/examples are used.

c. The approach of how theoretical material is explained, changes every year.

d. As support if you were sick and could not attend class.

e. To support staff and students at other universities who have challenges with staff or technical substance and depth.

f. To support engineers in industry with continuous professional development.

Specifically objectives (a) and (d) above are of relevance to you.

8. WHAT TO EXPECT OF ME AS A LECTURER

I undertake to:

a. share with you my knowledge and experience and, in doing so, prepare you for practice;

b. attempt to establish a love for the subject within you and aid your academic development;

c. hand out test results as soon as possible (in most cases the following day);

d. be well-prepared for formal lectures;

e. do everything in my ability to explain the work to you as well as possible and to make it as understandable as possible;

f. treat you in a professional manner;

g. be fair and courteous towards you at all times;

h. never humiliate you for asking a question during lectures (even if you and/or your class-mates should regard it as a 'stupid' question);

i. do everything in my power to help you pass the course.

9. WHAT I EXPECT OF YOU AS A STUDENT

I expect you to:

a. work VERY hard

b. show loyalty and integrity;

c. be dutiful and enthusiastic in your work;

d. behave in a disciplined manner in class;

e. discuss any problems you may experience with regard to the subject with me as soon as possible;

f. ask questions freely during lectures;

g. act professionally.

10.STUDY MATERIALS AND PURCHASES

Prescribed books:
Fluid Mechanics*, 8th Edition,* Frank M White, McGraw-Hill, ISBN 978-9-814-72017-5, 2016.

Heat and Mass Transfer, Fundamentals and Applications*: 5th Edition,* Yunus Çengel and Afshin Ghajar, McGraw-Hill, ISBN-13: 978-981-4595-27-8, 2015

11. PRINTING ERRORS IN THE TEXTBOOK OF CENGEL

Errata and for more recent updates check:
http://highered.mheducation.com/sites/0073398187/information_center_view0/errata___text.html

It is important that you make these changes to ensure you use the correct formulas, graphs, etc., in the tests and exams. We cannot take responsibility if you use the incorrect version in tests and exams. This information is given to ensure that you are aware of the changes that should be made.

12. LEARNING ACTIVITIES

12.1. Contact time and learning hours

Number of lectures per week: 3
Number of tutor classes per week: 1
Laboratory work: Three practical sessions of approximately one hour each.

This module carries a weighting of 16 credits, indicating that on average a student should spend some 160 hours to master the required skills (including time for preparation for tests and examinations). This means that on average you should devote some 10 hours of study time per week to this module. The scheduled contact time is approximately three hours per week, which means that another seven hours per week of own study time should be devoted to the module.

12.2. Lectures

Lectures do not cover all the textbook material; they concentrate on central themes and examples. In order to improve comprehension, parts of the class discussion are based on alternative sources. However, students can base their studies on the textbook and the class notes. The examples in the textbook are most important and must be carefully studied.

In the class discussions the lecturer identifies those parts of the course material which he regards as of primary importance. These topics are often further clarified through alternative sources. Central themes are explained. Obviously, test and the examination tend to concentrate on the issues which are discussed in the lectures; but, a few questions are also included to measure the self-tuition efforts of students. Students who are absent from lectures must decide for themselves which parts of the course material are more important. These students are clearly at a disadvantage and will have to work a lot harder. The most efficient way of studying heat transfer is to attend all lectures fully prepared, and to follow the discussion carefully. Students attending lectures unprepared will derive much less benefit. The lecturer assumes that, at least, the particular sections of the textbook that are being discussed, as well as the examples, and the problems at the end of the particular chapter, have been read through carefully.

Do not hesitate to ask questions during the lecture.

12.3. Assignments

For every chapter, homework is assigned. The homework will be assessed in a class test.

12.4. Laboratory work

There are three practical sessions. It is a precondition for admission to the final examination that ALL the practicals be passed. The practical guide gives more information about the experiments.

Students are expected to prepare for each practical session. A short report on each experiment must be handed in. The reports must state very briefly the goal, theory, results obtained and a conclusion for each experiment. The minimum mark for a practical report is 50%. Marks below 50% are discarded and the report must be corrected.

13. RULES OF ASSESSMENT

To be admitted to write exam:

1. obtain a semester mark of 40% and higher

and

2. obtain a subminimum of 50% for every practical

and

3. also attend all the scheduled laboratory sessions.

Pass requirements: In order to pass this module a student must

1. obtain a final mark of at least 50%

and

2. obtain a subminimum of 50% for each practical and also attend all the scheduled laboratory sessions.

Calculation of the final mark: The final mark is calculated as follows:

Semester mark:	50%
Examination mark:	50%

Calculation of the semester mark: The semester mark is compiled as follows:

Semester tests	60%
Laboratory work	10%
Class tests on assignments	30%

Semester tests. Two tests of 90 minutes each will be written during the scheduled test weeks of the School of Engineering. Dates, times and venues will be announced as soon as the timetables become available. The semester tests and exam are open book and therefore it is a requirement that you bring with you the two prescribed test books of Cengel and White.

14.HANDING IN OF PRACTICAL REPORTS

All practical reports should be submitted within seven days after a chapter was completed (or seven days after the practical was conducted).

15. GENERAL

This study guide is part of the official study guide of the Department.

I trust you will enjoy the lectures and your studies and complete the course with great success!
All the best!

STUDY COMPONENT

16. MODULE OBJECTIVES, ARTICULATION AND LEARNING OUTCOMES

16.1. General objectives

Heat transfer is not a difficult subject. The level of abstraction in the basic concepts is quite low, and the required level of mathematical skill is not high. Students who are familiar with solution of the basic partial differential equations, of e.g. fluid flow, should experience no difficulty. It is assumed that students are capable of solving standard differential equations and are familiar with surface- and volume integrals, as well as matrices. The solution of the diffusion equation, through the separation of variables technique, and other boundary value problems, are discussed briefly in the lectures. Students who are knowledgeable of the solution of two-dimensional potential problems with complex analysis will derive benefit from this knowledge, but no complex number algebra is used in the lectures.

The “art” of studying heat transfer successfully, is to absorb a large number of new concepts quickly, and to learn to discriminate between the huge variations of problems. The variations are caused by the different mechanisms of heat transfer (conduction, convection, radiation, latent heat, etc.), and the complications caused by many different physical geometry’s. In addition, a great deal of empirical knowledge (mainly concerned with convection), must be integrated with the fundamental principles. Please note that it is impossible to absorb these details a few hours before a test or examination. The best way of preparation is to learn to discriminate between various cases by attempting to do as many problems as possible. Students who diligently work, and each week make certain that they understand the work, should succeed with good results.

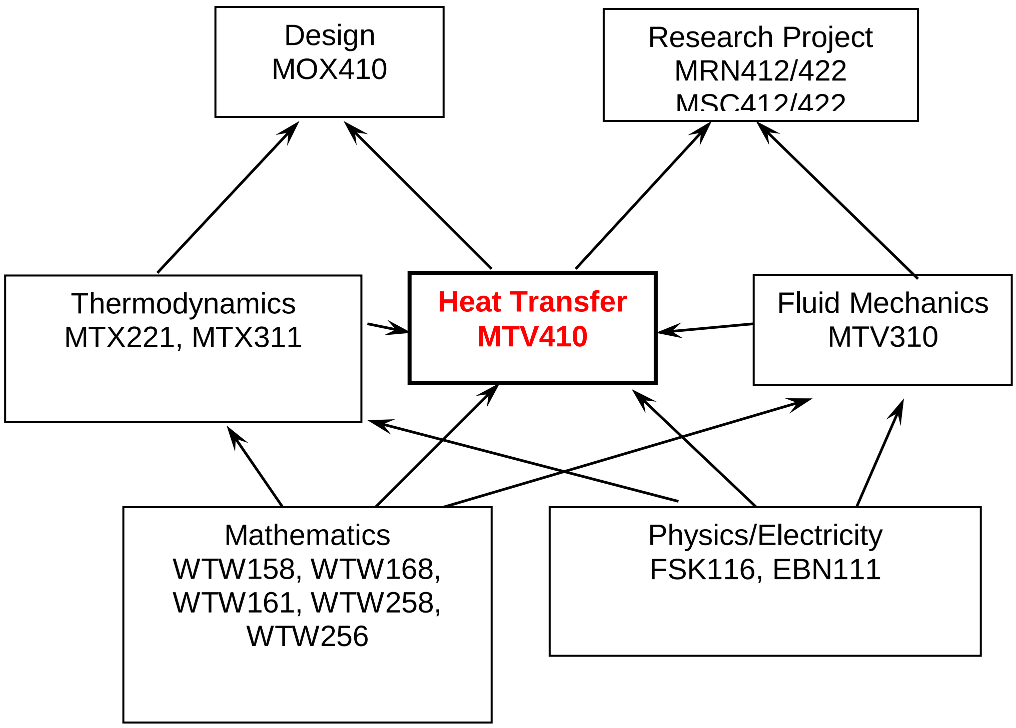
Due to the large number of concepts, and many details, comprehensive discussion of the subject matter in the lectures is impossible. The lectures concentrate on central themes and are to be regarded as supplementary to the prescribed textbook. The textbook is not discussed in the lectures, but is used for self-tuition. Self-tuition is the most important component of the course. Students who fail to prepare themselves for the lectures will not derive much benefit from attendance. On the other hand: no student who fails to attend the lectures can expect to do well. In the lectures important concepts are pointed out and explained.

Tests and the examination are intended to measure the students' understanding of basic principles, and to evaluate the insight and capability of students to solve specific problems. Evaluation is always based on the study goals that follow later in this study guide.

16.2. Prerequisite learning

The subject is presented late in the mechanical engineering curriculum because it is to a large extent based on prior knowledge from other subjects. For conduction, students must have knowledge of the solution of partial differential equations. Convection is based on fluid flow (boundary layer theory). Radiation is based on quantum mechanical principles of electro-magnetic radiation.

16.3. Articulation with other modules in the programme



17. MODULE STRUCTURE

Study theme and Study units	**Mode of instruction**	**Learning hours**	**Contact session: estimated**
Differential relationships for fluid flow Acceleration field of a fluid Differential equation of mass conservation Differential equation of linear momentum Differential equation of angular momentum	Lectures Problems in class Self-study	20	5

Differential equation of energy Boundary conditions Stream function Vorticity and irrotationality Frictionless irrotational flow Incompressible viscous flows			
Transient heat conduction **Take note: the relevant content of this Chapter has been changed significantly and should not be compared (especially tests and examinations) with 2002 - 2018** Lumped systems analysis Transient heat conduction in large plane walls, long cylinders, and spheres with spatial effects ~~Heisler charts~~ ~~Transient heat conduction in semi-infinite solids~~ ~~Transient heat conduction in multidimensional systems~~	Lectures Problems in class Self-study	20	3
Fundamentals of convection Physical mechanism of convection Classification of fluid flows Velocity boundary layer Thermal boundary layer Laminar and turbulent flows Heat and momentum transfer in turbulent flow Derivation of differential convection equations Solutions of convection equations for a flat plate Non-dimensionalized convection equations and similarity Functional forms of friction and convection coefficients Analogies between momentum and heat transfer (Additional notes on the results of recent research provided)	Lectures Problems in class Self-study	27	4
External forced convection Drag and heat transfer in external flow Parallel flow over flat plates Flow across cylinders and spheres Flow across tube banks	Lectures Problems in class Self-study	24	5
Internal forced convection Introduction Average velocity and temperature The entrance region (Additional notes on the results of recent research provided) General thermal analysis Laminar flow in tubes Turbulent flow in tubes Mixed convection (Additional notes on the results of recent research provided)	Lectures Problems in class Self-study	18	7

Natural convection Physical mechanism of natural convection Equation of motion and the Grashof number Natural convection over surfaces Natural convection from finned surfaces Natural convection inside enclosures Combined natural and forced convection (Additional notes on the results of recent research provided)	Lectures Problems in class Self-study	9	4
Heat exchangers Types of heat exchangers The overall heat transfer coefficient Analysis of heat exchangers The log mean temperature difference method The effectiveness – NTU method Selection of heat exchanger	Lectures Problems in class Self-study	21	5
Radiation heat transfer Thermal radiation Blackbody ration Radiation intensity Radiative properties Atmospheric and solar radiation View factor View factor relations Radiation heat transfer: black surfaces Radiation heat transfer: diffuse, gray surfaces Radiation shields and radiation effect Radiation exchange with emitting and absorbing gasses	Lectures Problems in class Self-study	21	3
Total		**160**	**36**

The notional hours include the contact time, as well as the estimated time allowed for preparation for tests and exams

18.STUDY THEME DESCRIPTIONS

STUDY THEME 1: DIFFERENTIAL RELATIONS FOR FLUID FLOW
Study unit: White Chapter 4

Outcomes

When you finish studying this chapter, you should be able to:
Derive the continuity equation (Cartesians coordinates).
Be able to use the continuity, momentum and energy equation to solve and derive simple analytical solutions.
Understand what a stream function is and be able to solve basic flow fields with it.
Understand what vorticity and irrotationality are, and be able to calculate it from a given flow field.
Derive Couette flow between two plates, and be able to solve practical problems using it.
Derive fully developed laminar pipe flow, and be able to solve practical problems using it.

Assignments to be assessed.

Problems: Refer to class examples

STUDY THEME 2: TRANSIENT HEAT CONDUCTION
Study unit: Çengel and Ghajar: Chapter 4

Outcomes
As specified by Çengel and Ghajar: : "When you finish studying this chapter, you should be able to:

Assess when the spatial variation of temperature is negligible, and temperature varies nearly uniformly with time, making the simplified lumped system analysis applicable,
Use analytical solutions for transient one-dimensional conduction problems in rectangular, cylindrical, and spherical geometries using the method of separation of variables, and understand why a one-term solution is usually a reasonable approximation,
Solve the transient conduction problem in large mediums using the similarity variable, and predict the variation of temperature with time and distance from the exposed surface"

Assignments to be assessed
Problems: 4.16, 4-22, 4-30, 4-50, 4-55, 4-56

STUDY THEME 3: FUNDAMENTALS OF CONVECTION
Study unit: Çengel and Ghajar: Chapter 6

Outcomes
As specified by Çengel and Ghajar: : "When you finish studying this chapter, you should be able to:

Understand the physical mechanism of convection, and its classification,
Visualize the development of velocity and thermal boundary layers during flow over surfaces,
Gain a working knowledge of the dimensionless Reynolds, Prandtl, and Nusselt numbers,
Distinguish between laminar and turbulent flows, and gain an understanding of the mechanisms of momentum and heat transfer in turbulent flow,
Derive the differential equations that govern convection on the basis of mass, momentum, and energy balances, and solve these equations for some simple cases such as laminar flow over a flat plate,
Nondimensionalize the convection equations and obtain the functional forms of friction and heat transfer coefficients, and
Use analogies between momentum and heat transfer, and determine heat transfer coefficient from knowledge of friction coefficient."

Assignments to be assessed
Problems: 6.8, 6.17, 6.42, 6.67, 6.75, 6.89, 6.101

STUDY THEME 4: EXTERNAL FORCED CONVECTION
Study unit: Çengel and Ghajar: Chapter 7

Outcomes
As specified by Çengel and Ghajar: "When you finish studying this chapter, you should be able to:

Distinguish between internal and external flow,
Develop an intuitive understanding of friction drag and pressure drag, and evaluate the average drag and convection coefficients in external flow,
Evaluate the drag and heat transfer associated with flow over a flat plate for both laminar and turbulent flow,
Calculate the drag force exerted on cylinders during cross flow, and the average heat transfer coefficient, and
Determine the pressure drop and the average heat transfer coefficient associated with flow across a tube bank for both in-line and staggered configurations."

Assignments to be assessed
Problems: 7.37, 7.51, 7.65, 7.94, 7.102, 7.105, 7.124

STUDY THEME 5: INTERNAL FORCED CONVECTION
Study unit: Çengel and Ghajar: Chapter 8

Outcomes
As specified by Çengel and Ghajar: "When you finish studying this chapter, you should be able to:

Obtain average velocity from a knowledge of velocity profile, and average temperature from a knowledge of temperature profile in internal flow,
Have a visual understanding of different flow regions in internal flow, such as the entry and the fully developed flow regions, and calculate hydrodynamic and thermal entry lengths,
Analyze heating and cooling of a fluid flowing in a tube under constant surface temperature and constant surface heat flux conditions, and work with the logarithmic mean temperature difference,
Obtain analytic relations for the velocity profile, pressure drop, friction factor, and Nusselt number in fully developed laminar flow, and
Determine the friction factor and Nusset number in fully developed turbulent flow using empirical relations, and calculate the pressure drop and heat transfer rate. "

Additional outcomes based on recent published research:
Have a visual understanding of forced and mixed convection internal flow and criteria to be able to distinguish between forced and mixed convection (also Chapter 9).
Determine the Nusselt numbers and friction factors for mixed convection.

Assignments to be assessed
Problems: 8.23, 8.44, 8.62, 8.76, 8.87, 8.97, 8.103

STUDY THEME 6: NATURAL CONVECTION
Study unit: Çengel and Ghajar: Chapter 9

Outcomes
As specified by Çengel and Ghajar: : "When you finish studying this chapter, you should be able to:

Understand the physical mechanism of natural convection,
Derive the governing equations of natural convection, and obtain the dimensionless Grashof number by nondimensionalizing them,
Evaluate the Nusselt number for natural convection associated with vertical, horizontal, and inclined plates as well as cylinders and spheres,
Examine natural convection from finned surfaces, and determine the optimum fin spacing,
Analyze natural convection inside enclosures such as double-pane windows, and
Consider combined natural and forced convection, and assess the relative importance of each mode."

Additional outcomes based on recent published research:
Determine the convection flow regime from flow regime maps.

Assignments to be assessed
Problems: 9.45, 9.54, 9.57, 9.82, 9.83, 9.106, 9.139

STUDY THEME 7: HEAT EXCHANGERS
Study unit: Çengel and Ghajar: Chapter 11

Outcomes

As specified by Çengel and Ghajar: : "When you finish studying this chapter, you should be able to:

Recognize numerous types of heat exchangers, and classify them,
Develop a awareness of fouling on surfaces, and determine the overall heat transfer coefficient for a heat exchanger,
Perform a general energy analysis on heat exchangers,
Obtain a relation for the logarithmic mean temperature difference for use in the LMTD method, and modify it for different types of heat exchangers using the correction factor,
Develop relations for effectiveness, and analyze heat exchangers when outlet temperatures are not known using the effectiveness-NTU method,
Know the primary considerations in the selection of heat exchangers."

Assignments to be assessed:
Problems: 11.24, 11.49, 11.51, 11.88, 11.97, 11.110, 11.141

STUDY THEME 8: RADIATION HEAT TRANSFER
Study unit: Çengel and Ghajar: Chapter 12 and Chapter 13

Outcomes
As specified by Çengel and Ghajar: : "When you finish studying this chapter, you should be able to:

Calculate the fraction of radiation emitted in a specified wavelength band,
Understand the properties emissivity, absorptivity, reflectivity and transmissivity,
Calculate view factor,
Obtain relations for net rate of radiation heat transfer between enclosure surfaces."

Assignments to be assessed:
Problems: Refer to class examples

19.PRACTICALS

There are four experiments that should be completed.

Practical	Description
1	Transient heat conduction
2	Heat conduction
3	Heat exchangers
4	Heat exchangers

Take note of the contact details of the TA's in section 6

The practical sessions are attended in groups of five to six persons. Book your practicals via the information provided in the announcement.

PRACTICAL 1: TRANSIENT HEAT CONDUCTION

1. Goal

The goal of the practical is to observe unsteady state conduction of heat to the centre of a solid sphere when a step change is applied to the temperature at the surface of the shape; and by using analytical transient-temperature charts to determine the conductivity of a solid sphere from measurements taken on a similar sphere but having a different conductivity.

2. Preparation

a. Read and understand the principles of transient heat conduction (Cengel §4) with emphasis on transient heat conduction in spheres with spatial effects (Cengel §4-2).
b. Review convection, its determining factors and concepts such as the Biot number and Fourier number.
c. A short quiz will be held at the beginning of the session to ensure preparation. Failure to display the required knowledge would result in the group being disallowed to perform the practical in that session.

3. Apparatus

A schematic representation of the apparatus appears in Figure 1 of the appendix. It consists of a heated water bath with a circulating pump and a flow duct in which the various shapes are placed. The shapes used for this experiment are a sphere 45 mm diameter manufactured in Brass and a sphere 45 mm diameter manufactured in Stainless Steel.

The heat transfer service unit serves as a power source for the circulating pump, data logger for the thermocouples and as computer-accessory interface.

Thermocouple T1 is located at the base of the flow duct, inside the water bath, and allows the temperature of the water to be monitored and adjusted to the required temperature before immersing the shapes.

Thermocouple T2 is mounted on the shape holder and contacts the hot water at the same instant as the solid shape does and provides an accurate datum for temperature/time measurements.

A Thermocouple T3 is installed permanently inside each of the solid shapes.

4. Experimental procedure

a. Adjust the thermostat on the water heater to setting '4' and check that the red light is illuminated indicating that power is connected to the heating element.
b. Set the voltage to the circulating pump to 12 Volts, using the control box on the mimic diagram software screen.
c. Allow the temperature of the water to stabilise (monitor the changing temperature T1 on the software screen).

d. The water must be in the range 80 - 90°C for satisfactory operation. If outside this range adjust the thermostat and monitor T1 until the temperature is satisfactory.
e. Attach the brass sphere to the shape holder (insert the insulated rod into the holder and secure using the transverse pin) but do not hold the metal shape or subject it to a change in temperature. Check that the thermocouple attached to the shape is connected to T3 on the service unit. Check that the thermocouple wire is located in the slot at the top of the shape holder.
f. Check that the temperature of the shape has stabilised (same as air temperature T2).
g. Switch off the electrical supply to the water bath (switch off the RCD on the connection box) to minimise fluctuations in temperature if the thermostat switches on/off.
h. Start continuous data logging by selecting the 'GO'icon on the software toolbar.
i. Allow the temperature of the shape to stabilise at the hot water temperature (monitor the changing temperature T3 on the mimic diagram software screen).
j. When temperature T3 has stabilised, select the'STOP' icon to end data logging.
    I. Create a new results sheet.
    II. Switch on the electrical supply to the water bath to allow the thermostat to maintain the water temperature.
    III. Remove the brass sphere from the shape holder then fit the stainless steel sphere.
    IV. Repeat the above procedure to obtain the transient response for the stainless steel sphere. Remember to create a new results sheet at the end, ready for the next set of results.

5. Questions

a. Plot the graph of T2 and T3 versus time for the brass sphere on a single graph.
b. Using the graphical solution, calculate the convection heat transfer coefficient 'h' assuming k = 121 W/m·K for brass.
c. Plot the graph of T2 and T3 versus time for the stainless steel sphere on a single graph.
d. Using the same method, for the second graph, calculate the thermal conductivity 'k' for the stainless steel sphere.
e. What conclusions can be drawn from the material properties of the respective spheres based on the above graphs?
f. Using the approximate analytical solution, determine the time duration for T_o to reach T_∞-20°C; T_o to reach T_∞-10°C; and T_o to reach T_∞-3°C. (Assume α= 3.7 x 10-5 m^2s^{-1} for brass and α= 0.6 x 10-5 m^2s^{-1} for stainless steel).

6. Report

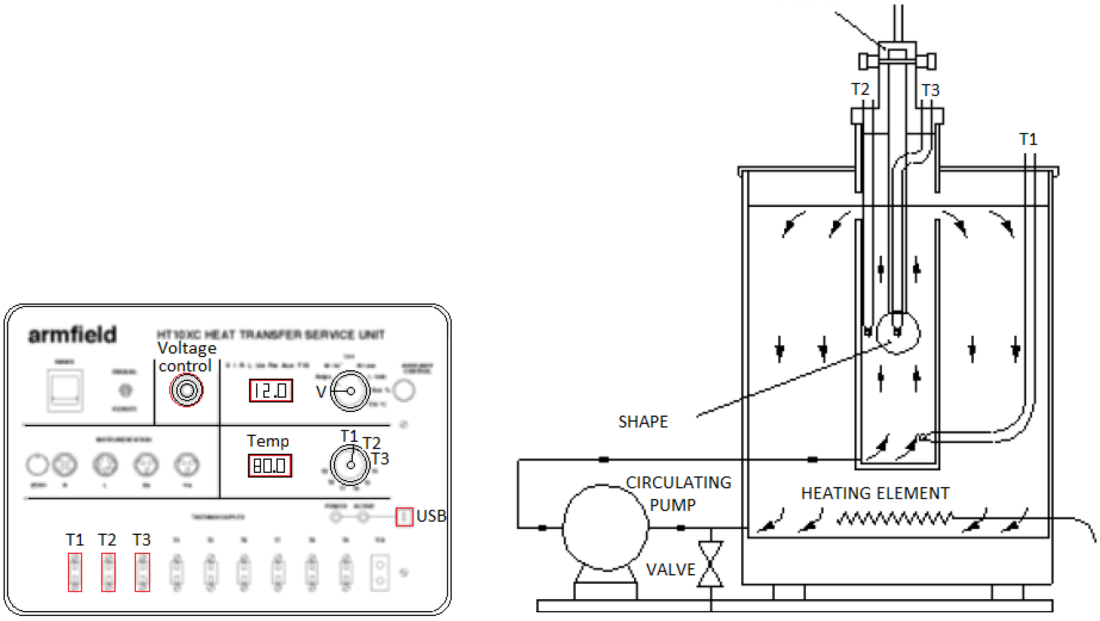
Hand in a complete report, containing sample calculations where relevant, and graphs of T3 & T2 versus time, for brass and stainless steel. The graphs should include the three analytically determined points as outlined in question 6. Answer all questions and discuss your results paying attention to the following points:

- Conductivity and diffusivity of the respective materials.

- What physical parameters of the experiment can be varied as to increase or decrease the time to reach steady state.
- Critically analyse the experimental setup and discuss its limitations.

Appendix:

Figure 1: Heat Transfer Service Unit and Unsteady Heat Transfer Accessory (Armfield, 2010)



Practical 2: Heat Conduction

1. Goal:

The aim of this experiment is to give the students the opportunity to investigate the application of the Fourier Rate equation for simple one dimensional steady-state conduction as well as introduce typical steady heat conduction calculations to determine the thermal conductivity of a certain material from the measured heat flow.

2. Preparation:

In preparation do the following:

a. Make certain you understand the principles of the general heat conduction equation and boundary conditions (Cengel § 2-2 up to and including § 2-5).
b. Make certain you understand the principles of steady heat conduction in plane walls as well as thermal contact resistance (Cengel § 3-1 and § 3-2).
c. Read Cengel § 3-3 to understand the concept of thermal resistances.
d. Review the principles of operation of thermocouples and review the operation of the Heat Transfer Service Unit (HT10XC – Appendix B).
e. A short quiz may be held at the beginning of the practical session to ensure preparation. If the group is insufficiently prepared they will not be allowed to do the practical in that session.

3. Apparatus:

The Linear Heat Conduction accessory consists of:

a. A heating section manufactured from a 25 mm diameter cylindrical brass bar with a cartridge type electrical heating element.
b. Intermediate sections incorporating different metal specimens as follows:
    I. 30 mm long brass specimen (25 mm diameter cylindrical bar), fitted with 2 thermocouples 15 mm apart.
    II. 30 mm long stainless steel specimen (25mm diameter cylindrical bar)
    III. 30 mm long aluminium alloy specimen (25mm diameter cylindrical bar)
    IV. 30 mm long brass specimen with reduced diameter (13mm diameter cylindrical bar)
c. A cooling section manufactured from a 25 mm diameter cylindrical brass bar which is cooled at one end be passing water through galleries in the section

Three thermocouples (T1, T2 and T3) are positioned along the heated section at uniform intervals of 15 mm. Three thermocouples (T6, T7 and T8) are positioned along the cooling section at uniform intervals of 15 mm. Two thermocouples (T4 and T5) are positioned along the brass intermediate section, also at 15 mm intervals. This can be seen in Figure 1.

These thermocouples measure the temperature gradient along the section to which they are attached. A schematic representation of the Linear Heat Conduction accessory can be found in Figure 2 and Figure 3 of Appendix A.

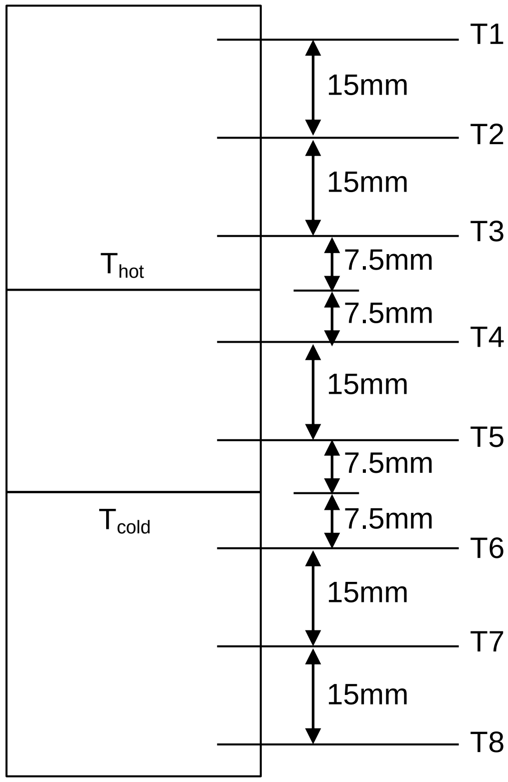


Figure 1: Thermocouple positions.

4. Experimental Procedure:

a. Clamp the intermediate section between the heated and cooled section of the Linear Heat Conduction accessory having lightly coated the mating faces with thermal paste.
b. Set the voltage of the heating section by adjust the voltage control potentiometer to give a reading of 12 V on the top panel display with the selector switch set to position V.
c. Allow the temperature reading to stabilize.
d. When the temperatures have stabilized use the lower selector switch on the console to set the console display to each temperature sensor in turn and record the following T1, T2, T3, T4, T5, T6, T7, T8, V, I and Fw.
e. Repeat steps (b) to (d) for 15 V and 17 V.

Follow steps (a) to (e) for the 25 mm diameter brass intermediate section (instrumented with two thermocouples)

Follow steps (a) to (e) for the 25 mm diameter aluminium alloy intermediate section.

5. Questions:

For each of the voltages for the 25 mm diameter brass intermediate section calculate the following:

a. Determine the heat flow (power input to the heater).
b. Determine the temperature difference across the heated section.
c. Determine the thermal conductivity of the heated section.
d. Determine the temperature difference across the intermediate section.
e. Determine the thermal conductivity of the intermediate section.
f. Determine the temperature difference across the cooled section.
g. Determine the thermal conductivity of the cooled section.
h. Compare the calculated value for the thermal conductivity of the brass in the three sections at the same heat flow.
i. Plot a graph of temperature against position along the bar and draw the best straight line through the points.
j. Calculate the average thermal conductivity of the brass bar using the gradient of each straight line and the corresponding heat flow through the bar. Compare the value obtained with the values previously obtained for each individual section of the bar and comment on any difference.

For each of the voltages for the 25 mm diameter aluminium alloy intermediate section do the following:

a. Determine the heat flow (power input to the heater).
b. Determine the temperature of the hot surface of the intermediate section (Thot).
c. Determine the temperature of the cold surface of the intermediate section (Tcold).
d. Determine the temperature difference across the intermediate section.
e. Determine the thermal conductivity of intermediate section.
f. Determine the total resistance to heat flow.

$$U = \frac{Q}{A(T_1 = T_8)}$$

g. Determine the overall heat transfer coefficient.
h. Compare the two values obtained for the Overall Heat Transfer Coefficient U and U = 1/R and comment on any difference in the values obtained.
i. Compare the values obtained for the thermal conductivity of intermediate section at the different settings of heat flow through the specimen.
j. Plot a graph of temperature against position along the bar and draw the best straight line through the points for the heated section and cooled section. Extrapolate each line to the joint with the intermediate section then join these two points to give the gradient through the intermediate section.
k. Calculate the average thermal conductivity of the aluminium alloy bar using the temperature gradient of each straight line and the corresponding heat flow through the

intermediate section. Compare with previous values obtained and comment on any difference

6. Report:

Hand in a complete report covering all of the questions mentioned above. Include one sample calculation for each question.

Discuss your results paying special attention to the following points:

a. What was the effect of varying the heater power, if any?
b. Temperature gradients of the different materials.

Appendix A:

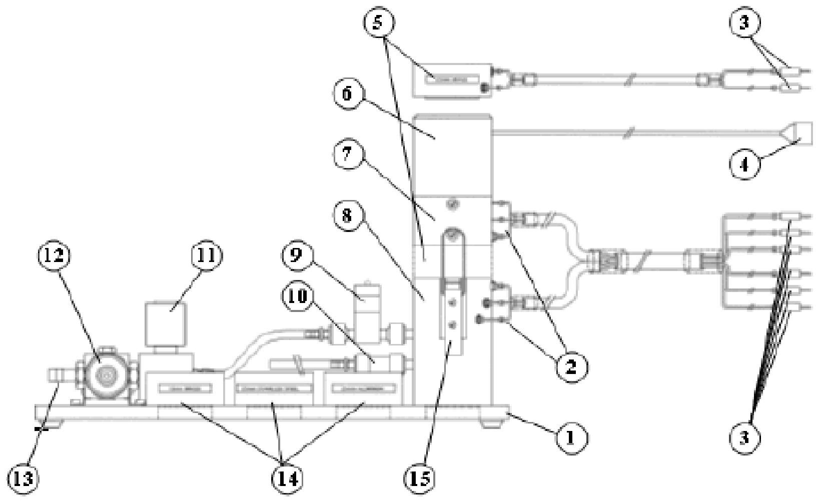


Figure 1: Side view of Linear Heat Conduction accessory (Armfield, 2010)

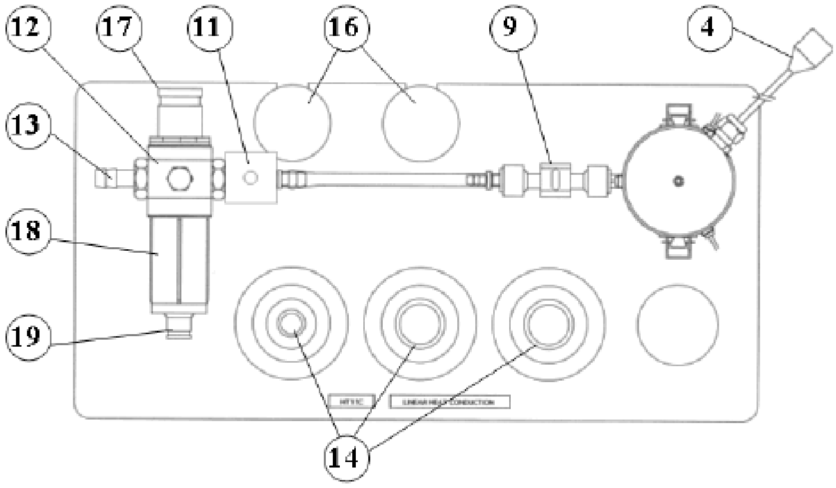


Figure 2 Top View of HT11C

Figure 2: Top view of Linear Heat Conduction accessory (Armfield, 2010)

2)Thermocouples

3) Miniature thermocouple plug

5) 30 mm long brass specimen (25 mm diameter cylindrical bar), fitted with 2 thermocouples

6) Heating element

7) Heating section

8) Cooling section

14) Intermediate sections (described in part 3 of this guide)

15) Toggle clamps

16) Cold water inlet

Appendix B:

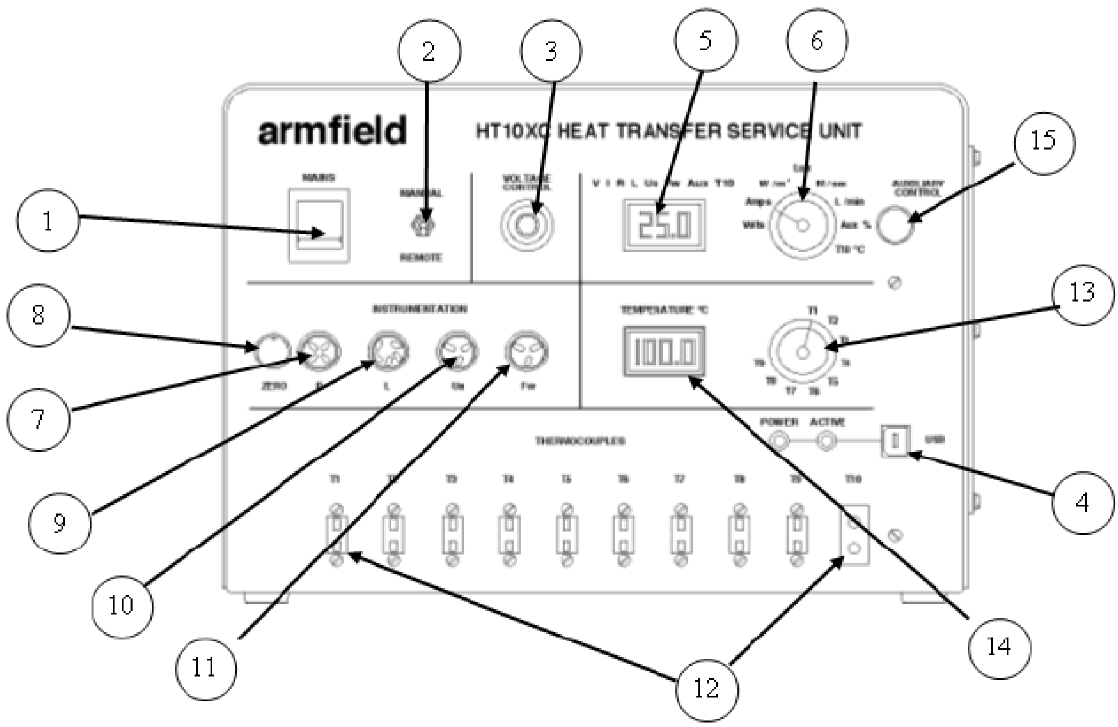


Figure 1: Front view of Heat Transfer Service Unit (Armfield, 2010)

1) Mains standby switch

2) Manual / Remote switch

3) Multi-turn potentiometer

5) Top panel meter

6) Measurement selector switch

11) Cooling water flow sensor is connected to the socket marked Fw

12) Thermocouple socket

13) The required temperature reading is selected via a switch

14) Adjacent panel meter

15) The Auxiliary drive potentiometer

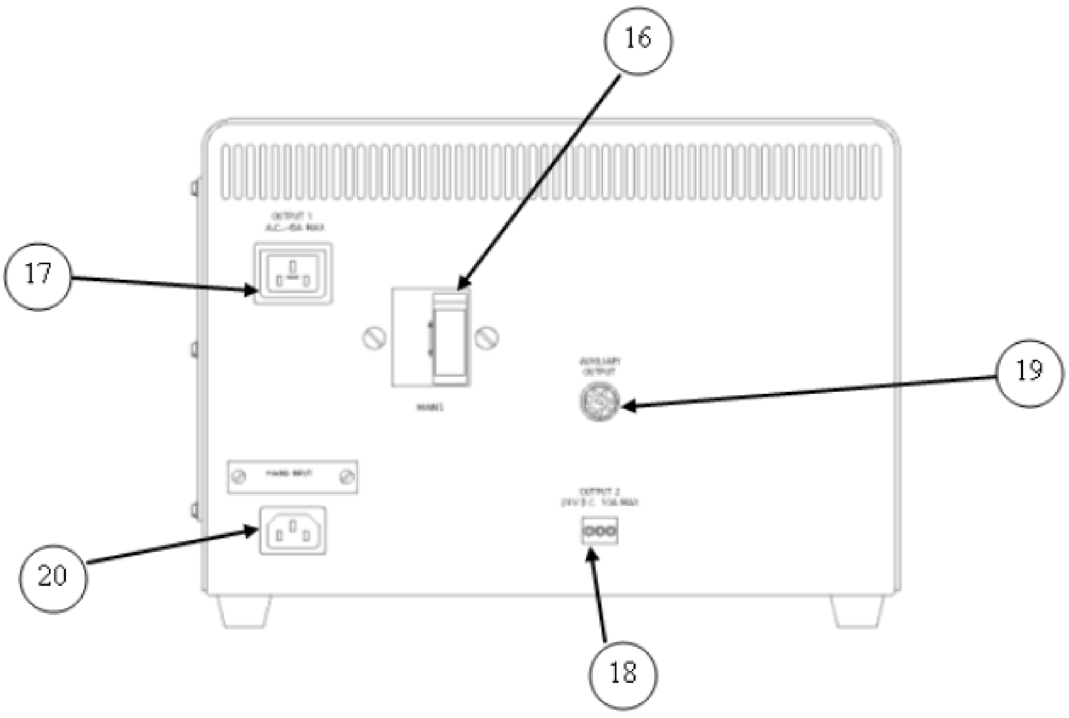
16) The Residual Current Circuit Breaker

17) The mains power output socket

18) The low voltage DC export socket

19) The auxiliary output

20) The mains power input socket



(Armfield, 2010)

Practical 3 and 4: Heat Exchangers (presented together in one practical session)

1. Goal

Investigate and assess the different types and methodologies of heat exchangers. To introduce typical characteristics necessary, for example the overall heat transfer coefficient and energy balance analysis of heat exchangers. Demonstrate the heat transfer process using different heat exchangers.

2. Preparation

Read and understand principles of operation of the different heat exchangers (Cengel §11-1 to §11-5). In addition, read Cengel §8-5 and §8-6 to understand the relationship between Reynolds number and Nusselt number.

A short quiz will be held at the beginning of the session to ensure that proper preparation is done. If the group is insufficiently prepared they will not be allowed to do the practical in the session.

3. Apparatus

3.1. Plate heat exchanger (Practical 4)

A schematic representation of the plate heat exchanger in a counterflow configuration appears in Figure 1. Hot and cold water flow on either side of the plates to promote heat transfer. Table 1 is the technical data needed to do calculations in conjunction with the experimental data you obtain from the practical session for the plate heat exchanger.

Table 1: Technical data for plate heat exchanger

Number of active plates	5
Plate overall dimensions	75 mm x 115 mm
Effective diameter	3 mm
Plate thickness	0.5 mm
Wetted perimeter	153 mm
Projected heat transfer area	0.008 m^2 per plate
Correction factor for LMTD	0.95

3.2. Shell and tube exchanger (Practical 3)

This type of exchanger consists of a number of tubes in parallel enclosed in a cylindrical shell. Heat is transferred between one fluid stream flowing through the tubes and another fluid stream flowing through the cylindrical shell around the tubes. A schematic representation of the shell and tube heat exchanger appears in Figure 2. The exchanger is operated in counterflow configuration.

Table 2: Technical data for shell and tube heat exchanger

Number of tubes	7
Heat transfer length of each tube	0.144 m
Tube inside diameter	0.00515 m
Tube outside diameter	0.00635 m

The specific heat capacity and density appears in Table 3 and Table 4 in the Appendix, respectively, for both heat exchangers.

4. Experimental procedure

a. Adjust the water flow rate to lit/min for the cold water side and 2.5 lit/min for the hot side.
b. Wait for conditions to reach steady state. Check that temperature readings are realistic.
c. Log the flow- and temperature readings.
d. Repeat procedure at 3 different flow rates.

5. Questions

a. Determine the heat balance for the heat exchangers through measurements of the temperatures and mass flow rates of the fluids.
b. Determine the effective heat transfer areas and LMTD between the two fluids.
c. Determine the overall heat transfer coefficients (h).
d. Determine the mean temperature efficiency.
e. Determine the Reynolds number (Re) and Nusselt number (Nu).
f. Determine the number of transfer units (NTU) and effectiveness (ε) of the shell and tube heat exchanger only.
g. Plot on a graph Nu versus Re and h versus Re

6. Report

Hand in a complete report containing one sample calculation for h and Nu. Include the graphs from (g) and also plot LMTD, Nu and ε versus Reynolds number. Discuss your results paying attention to the following points:

- Critically analyse the experimental set-up and discuss its limitations.
- Comment on the effects of changing in the cold water side flow rate and what would you expect if we change the hot water side flow rate.
- Comment in the effect of countercurrent flow versus concurrent flow.
- Compare on the performance of the plate heat exchanger in comparison to the shell and tube heat exchanger and comment on the differences.

- Comment on what could be expected if the working fluid changed.

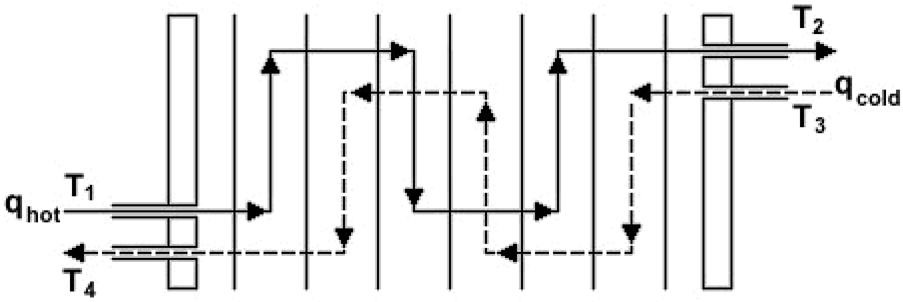


Figure 1: Counter current plate heat exchanger (Armfield, 2010)

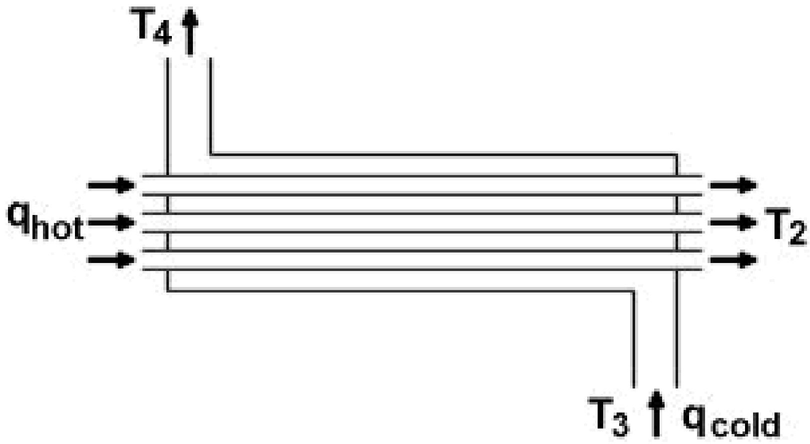


Figure 2: Schematic of the shell and tube heat exchanger (Armfield, 2010)

PRACTICAL 5: EXTENDED TUBULAR HEAT EXCHANGER *

*** This practical is only listed here for future use**

1. Goal

The goal of this experiment is:

- To demonstrate the differences between parallel and counter volume fluid flows in tubular heat exchangers;
- To determine the Overall Heat Transfer Coefficient using the Logarithmic Mean Temperature Difference (LMTD) method;
- Investigate the effect of changes in hot and cold fluid flow rates on the Temperature Efficiencies and Overall Heat Transfer Coefficients.

2. Preparation

To prepare for the practical, do the following:

- Read Cengel 11.1 – 11.5 (included).
- Make certain that you understand the principle of operation of the heat exchanger and the calculation of U-value, LMTD, NTU and $\dot{Q}$ to characterise the heat exchanger. You need to understand the calculation of $\dot{Q}$ for various fluid flow speeds. You must be able to analyse both parallel- and counter flow configurations.
- Identify the equations in Tables 11.4 and 11.5 which are applicable.
- What do you understand by the properties of fluids that vary with temperature?
- Do you know what a balanced heat exchanger is? Do you know how to calculate the LMTD in this case?
- How do you measure the temperature of a fluid in a tube?
- What is the principle of operation of a rotameter?

3. Apparatus

The Extended Tubular Heat Exchanger consists of two thin walled concentric (co-axial) tubes, exchanging heat via a metal (stainless steel) wall from the inner tube to the outer annulus, carrying the hot and cold fluid streams, respectively (figure 1).

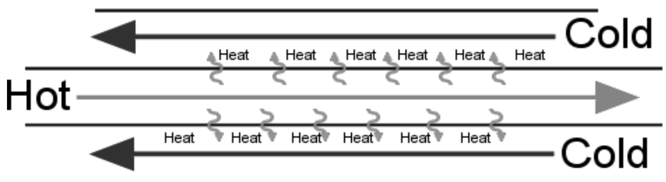


Figure 1: Heat Transfer process (Armfield, 2010)

The cold fluid stream flows either in the same direction as the hot fluid stream (parallel or concurrent flow) or in the opposite direction (counter or countercurrent flow) of four adjustable sets of concentric tubes, arranged in series in the form of a coil (figure 2 and 3).

This configuration has significantly reduced the overall length of the tubes and allowed measurement and monitoring of the temperature along both fluid streams.

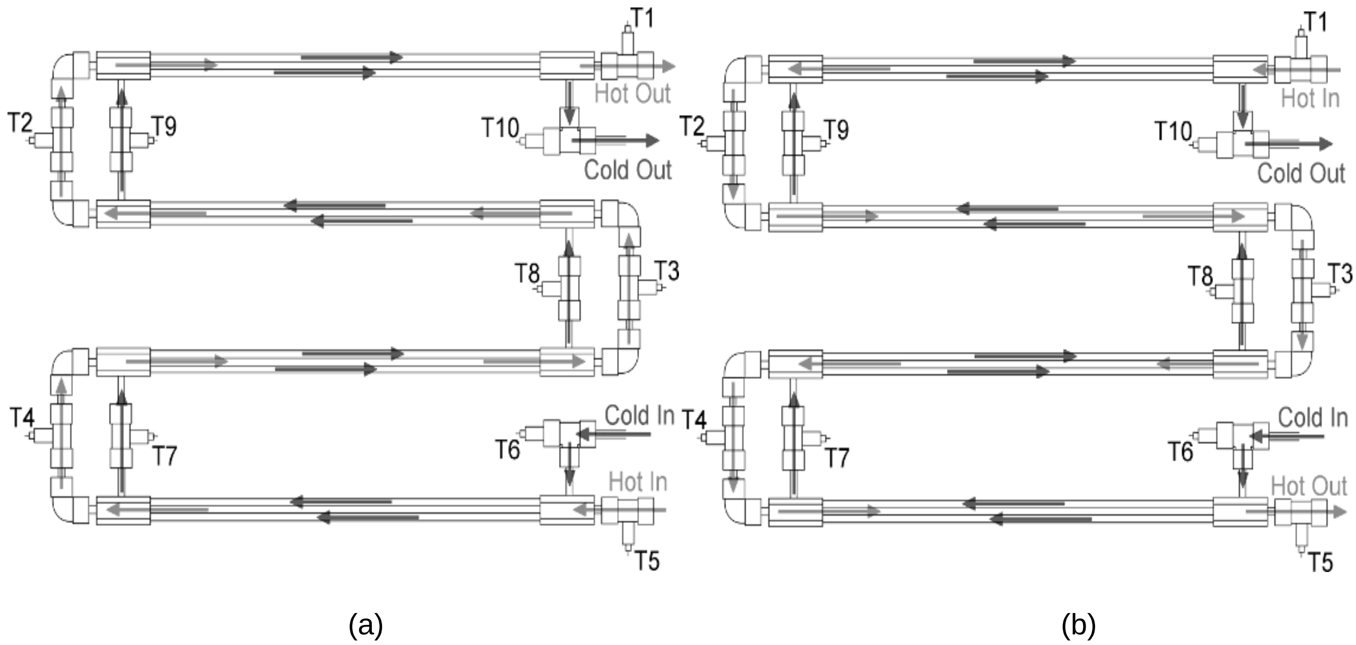


Figure 2: Flow configuration (a) Parallel flow; (b) Counter flow (Armfield, 2010)

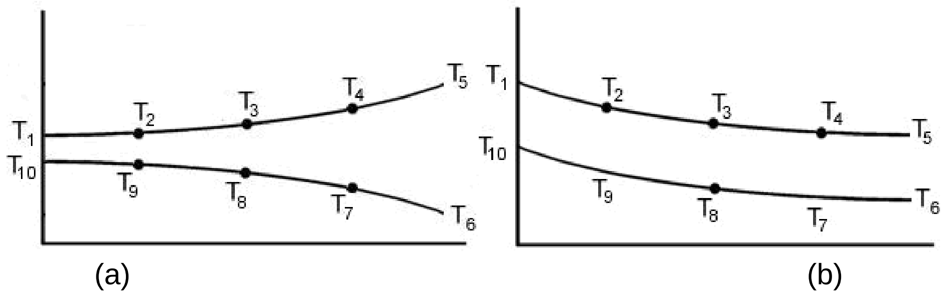


Figure 3: Temperature profile (a) Parallel flow; (b) Counter flow

Note: This arrangement minimizes heat loss from the inner stainless steel tube to the clear outer tube without the need for additional insulation.

The water flow rates are measured with rotameters, whereas the inlet and outlet temperatures of water are measured with semi-conductor heat sensors, which are placed inside the fluid stream. In addition, a set of valves allows both parallel and counterflow configurations.

4. Experimental Procedure

Using the software:

a. In the “number of tubes” box, select “4”.
b. In the “control” box, set “power on”.
c. Set the “cold flow rate” to about 1 lit/min by adjusting the arrows on the side of the cold water flow rate display box.

d. Click on the "Heater" control box and set:
   - Set the heater temperature to a set point of 50°C
   - Ensure that the "Proportional Band", the "Integral Time" and the "Derivative Time" are set to 5%, 200 s and 0 s, respectively.
   - Select "Automatic control"
   - Click on "Apply" and then "Ok" to close the controller window.

e. Click on the "Hot water flow" control box and set:
   - Set the hot water flow rate to a set point of 2 lit/min
   - Ensure that the "Proportional Band", the "Integral Time" and the "Derivative Time" are set to 100%, 3 s and 0 s, respectively
   - Select "Automatic control"
   - Click on "Apply" and then "Ok" to close the controller window.

f. Allow the temperatures at different stages of the heat exchanger to stabilise by monitoring it closely on the "mimic diagram display" (marked by "A" on figure 4 below). Then select "Sample Configuration" from the "Sample" menu on the top toolbar and select:
   - Select "Automatic Sampling Operation"
   - Set "Sample Interval" to 5 seconds.
   - Select "Continuous" Duration of Sampling.

g. Click on the "GO" icon to record the following:

Table 1: Results sheet for the countercurrent exercise

	Unit	Hot fluid	Cold fluid
Volume flow rate	(lit/min)	F_{hot}	F_{cold}
Inlet Temperature	^oC	T1	T6
Intermediate Temperature 1	^oC	T2	T7
Intermediate Temperature 2	^oC	T3	T8
Intermediate Temperature 3	^oC	T4	T9
Outlet Temperature	^oC	T5	T10

NOTE: The results sheet may be viewed by selecting the "Table" icon (marked by "B" on figure 5 below).

h. Adjust hot and cold volume flow rates to:

Table 2: Hot and cold flow rate variations

F_{hot} (lit/min)	F_{cold} (lit/min)
2	1
3	1
2	2
1	2
1	3

NOTE: Allow sufficient time for the flow rates to readjust to newly entered values. This may be monitored using the "Table" icon.

i. Click on the "Heater" control box and adjust the controller from "Automatic" to "Off". Click on the "Hot water flow" control box and adjust the hot water pump to the set point of 0 lit/min. Also set the cold water flow control valve to 0%.

j. Select "Save" from the "File" menu on the top toolbar to save your results sheet as:
   - File name: Counter_flow_GroupX
   - Save as type: Excel 4.0 or 5.0 file (*.xls)

k. Select "Load New Experiment" from the "File" menu, select the Cocurrent exercise. NOTE: The measurements for the concurrent exercise are as follows

Table 3: Results sheet for the concurrent exercise

	Unit	Hot fluid	Cold fluid
Volume flow rate	(lit/min)	F_{hot}	F_{cold}
Inlet Temperature	^{o}C	T5	T6
Intermediate Temperature 1	^{o}C	T4	T7
Intermediate Temperature 2	^{o}C	T3	T8
Intermediate Temperature 3	^{o}C	T2	T9
Outlet Temperature	^{o}C	T1	T10

l. Repeat steps 1 to 9 as for the countercurrent part of this practical. And later save your results sheet as:
   - File name: Parallel_flow_GroupX
   - Save as type: Excel 4.0 or 5.0 file (*.xls)

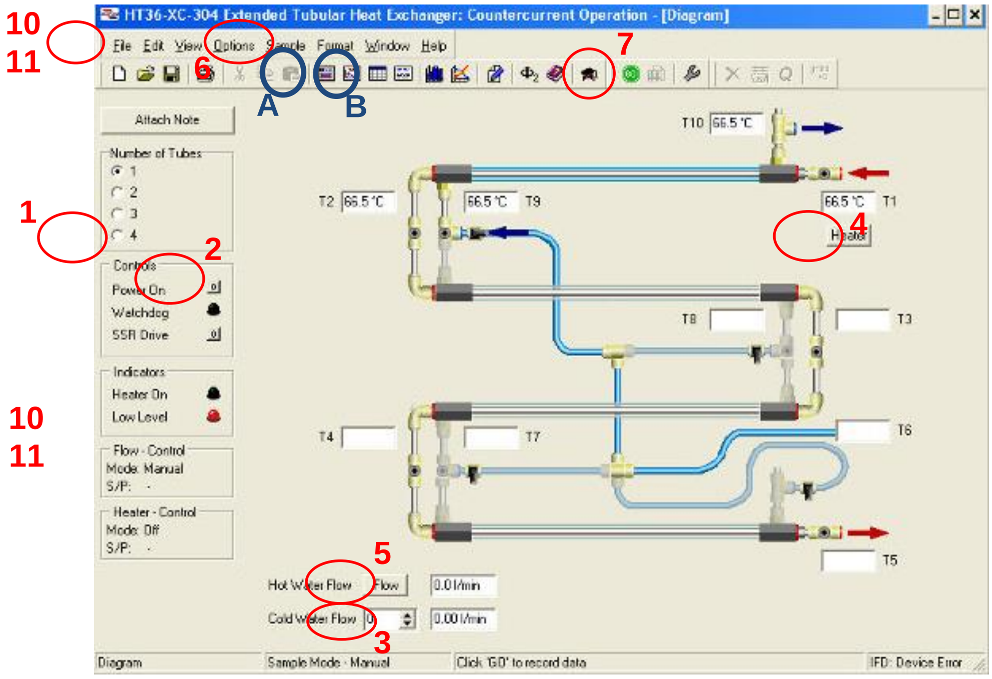


Figure 4: Software mimic diagram display (Armfield, 2010)

5. Questions

Complete the rest of the practical by finding the answers to the following questions:

a. For one set of measurements (of your choice), plot the temperatures at inlet, mid positions and outlet against position, for both parallel and counter flow.
b. Determine all fluid properties (Specific Heat, Density and Dynamic Viscosity) using the average fluid temperatures.
c. Using the fluid properties, determine the Reynolds Number for each set of measurements. Discuss your results.
d. Using the temperature changes and differences, calculate the heat energy transferred (emitted, absorbed and lost) and the temperature efficiencies. Discuss your results
e. Using different flow rate combinations of the hot and cold fluids, determine the LMTD and the corresponding Overall Heat Transfer Coefficient for each flow configuration. Discuss your results
f. Comment on the change in Δt_{hot} and Δt_{cold} when the heat exchanger is converted from parallel to counter flow configuration.

6. Report

The following must be included in a report on your practical: assumptions made, the measured results and conclusions that can be drawn from these results. In addition, compare the performance and comment on the differences between the tubular, plate and shell-and-tube heats exchangers.

Useful information:

Name	Symbol	SI Unit	Notes/Calculation
ID of tube	d_i	m	0.0083
OD of tube	d_o	m	0.0095
ID of shell	d_s	m	0.014
Arithmetic mean diameter of tube	d_m	m	$d_m = \frac{d_o + d_i}{2}$
Heat transmission length	L	m	0.330 per tube
Heat transfer area	A	m^2	$\pi \cdot d_m \cdot L$

Specific Heat Capacity of Water (Cp kJ/kg°K)

°C	0	1	2	3	4	5	6	7	8	9
0	4.1274	4.2138	4.2104	4.2074	4.2045	4.2019	4.1996	4.1974	4.1954	4.1936
10	4.1919	4.1904	4.1890	4.1877	4.1866	4.1855	4.1846	4.1837	4.1829	4.1822
20	4.1816	4.1810	4.1805	4.1801	4.1797	4.1793	4.1790	4.1787	4.1785	4.1783
30	4.1782	4.1781	4.1780	4.1780	4.1779	4.1779	4.1780	4.1780	4.1781	4.1782
40	4.1783	4.1784	4.1786	4.1788	4.1789	4.1792	4.1794	4.1796	4.1799	4.1801
50	4.1804	4.1807	4.1811	4.1814	4.1817	4.1821	4.1825	4.1829	4.1833	4.1837
60	4.1841	4.1846	4.1850	4.1855	4.1860	4.1865	4.1871	4.1876	4.1882	4.1887
70	4.1893	4.1899	4.1905	4.1912	4.1918	4.1925	4.1932	4.1939	4.1946	4.1954

Density of Water (ρ kg/m^3)

°C	0	2	4	6	8
0	999.8	999.9	999.9	999.9	999.9
10	999.7	999.5	999.2	998.9	998.6
20	998.2	997.8	997.3	996.8	996.2
30	995.7	995.0	994.4	993.7	993.0
40	992.2	991.4	990.6	989.8	988.9
50	988.0	987.1	986.2	985.2	984.2
60	983.2	982.2	981.1	980.0	978.9
70	977.8	976.6	975.4	974.2	973.0