THERMAL FLUID THEORY

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Keywords: Heat Transfer, Fluid Flow, Two Phases, Heat Exchangers

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Summary

When a working fluid is used in a thermodynamic cycle it must receive heat from a source and reject heat to a sink while producing work by expansion in a turbine. Associated with receiving and rejecting heat is heat transfer. This usually requires transfer of heat through a wall by conduction and transfer of this heat to or from the fluid by convection. If, at the heat source, heat is generated by combustion, a substantial amount of it is transferred to the wall by radiation. Thus all modes of heat transfer are important in thermal power plants. When water-steam is used as the working fluid it changes phase while receiving and rejecting heat so there is the further complication of boiling and condensing. This leads to two phase flow conditions where heat transfer may be enhanced or inhibited depending upon the rate of heat transfer.

Since the working fluid carries the heat energy from one part of the system to another, heat transport is also a consideration. The amount of heat that can be transported depends upon the ability of the fluid to store heat and its flow rate. For a given fluid, the greater the flow rate the greater the rate of heat transport. An increased flow rate however increases the fluid friction loss around the circuit so this has to be taken into account to avoid having to expend an excessive amount of energy on pumping. Two phase conditions affect the friction loss. Generally increased steam production increases the flow velocity and hence friction loss.

Wherever heat is transferred from one fluid to another through a wall there are also special considerations. Generally the temperature difference between the two fluids should be as small as possible to ensure good thermodynamic efficiency. The rate of heat transfer though depends upon this temperature difference, increasing with increased temperature difference and with increased surface area. Thus to minimize the temperature difference larger areas need to be utilized. This increases the capital cost so, in selecting a suitable heat exchanger, consideration has to be given to both thermodynamic and heat transfer performance.

1. Introduction

1.1. Heat Transfer

In a fossil fuel fired boiler or nuclear fueled reactor heat is generated by the fuel and transferred directly or indirectly to the working fluid of the thermodynamic cycle. This heat transfer may be by *conduction* through a solid, *convection* within a fluid or *radiation* from a surface. In the case of a fossil boiler the initial source of heat is the hot combustion gas while in a nuclear reactor it is the hot solid fuel. Very hot combustion gases readily transfer heat by radiation, all heat transfers through confining walls are by conduction, while convection is the dominant mode of heat absorption by the working fluid. If the working fluid changes phase there is the added complication of dealing with liquid and vapor mixtures. Heat transfer and the associated phenomena are therefore critical in the design and operation of boilers and reactors.

1.2. Fluid Flow

The working fluid in a steady flow thermodynamic cycle circulates around the system receiving heat from a fossil fired boiler or nuclear fueled reactor, doing work in a turbine and rejecting heat to the environment. During the heat transfer processes the fluid is in continuous motion so there is a strong relationship between heat transfer and fluid flow. At low velocities fluid flow may be *laminar* where layers of fluid flow smoothly over one another. At higher velocities fluid flow is usually *turbulent* where parcels of fluid follow an erratic path and there is mixing of the fluid. Turbulent flow enhances the transfer of heat to or from the flow as does agitation due to boiling. Once boiling occurs in fluid flow *two phase* conditions are established as opposed to *single phase* conditions which apply to the flow of water or vapor only.

2. Conduction

2.1 General Conduction Equation

One dimensional heat conduction q through a solid slab may be expressed by the following equation for rate of heat transfer Ω where T is temperature, x is thickness of the material, A is cross-sectional area and k is thermal conductivity:

$$\Omega = -k\,A\left(dT/dx\right)$$

$$q = -k\left(dT/dx\right)$$

For a finite thickness of material S this equation may be integrated to give:

$$q = k\left(T_1 - T_2\right)/S$$

Here T_1 is the temperature on the hot side and T_2 the temperature on the cold side of the slab. The thermal conductivity is assumed to remain constant with changing temperature. The difference in temperature ΔT across the slab is then given by:

$$\Delta T = q\,S/k \qquad (1)$$

In many practical applications the thermal conductivity of the material varies with temperature and a correction must be made so that an appropriate value is used under the prevailing conditions. Most materials used in heat transfer applications have good thermal conductivities so that the temperature change ΔT between the hot and cold surfaces is relatively small and using the thermal conductivity at the average temperature is quite accurate.

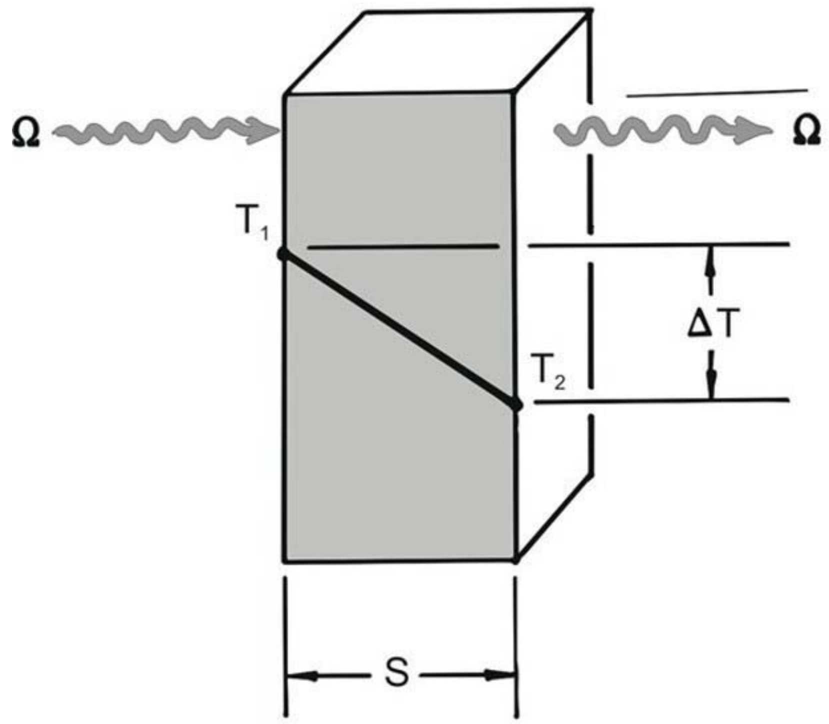

Figure 1: Heat conduction through a solid flat slab

2.2. Heat Generation and Conduction

Uniform heat generation and two-dimensional heat conduction in long cylindrical nuclear fuel elements are important applications of the basic heat transfer equation.

One dimensional heat conduction with uniform rate of heat generation q^* in a solid cylinder may be expressed by the following equation:

$$q^* = -k\left(d^2T/dx^2\right)$$

Converting to cylindrical co-ordinates where r is the radius gives:

$$q^* = -(k/r)(d/dr)\left[r(dT/dr)\right]$$

For an infinitely long cylinder of diameter D this equation may be integrated to give:

$$q^* = \left(16k/D^2\right)(T_0 - T_1)$$

Here T_0 is the temperature in the centre and T_1 the temperature at the surface. The difference in temperature ΔT between the centre and the surface is then given by:

$$\Delta T = q^* D^2/16k \qquad (2)$$

If this equation is required in terms of a rate of heat transfer q, the amount of heat generated in a given volume of cylindrical rod can be assumed to leave the rod through its exposed surface *A*. This gives the following equation:

$$\Delta T = q\,D/4\,k \quad (3)$$

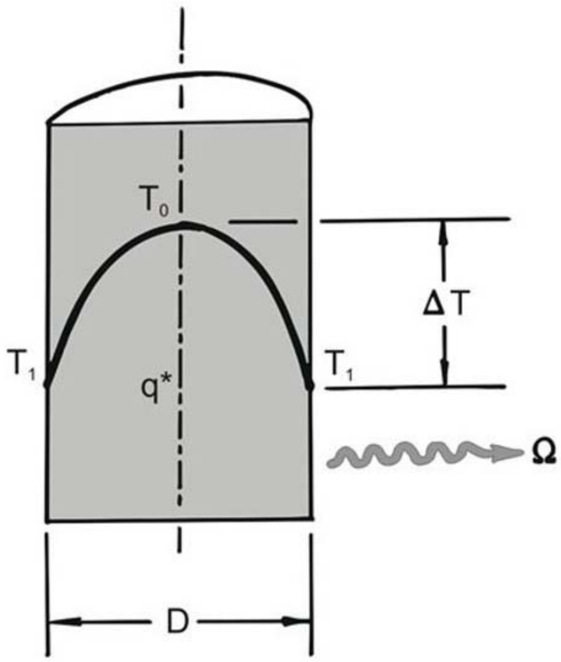

Figure 2: Heat conduction through a solid cylindrical rod

2.3. Heat Conduction through Cylindrical Walls

Another important application of the basic heat transfer equation is that of conduction through the cylindrical walls of pipes. In this case, where the radius is *r* and the pipe length *L*, the equation becomes:

$$\Omega = -k\,2\pi\,r\,L\left(dT/dr\right)$$

For a pipe of finite dimensions, that is, inside radius r_1 and outside radius r_2, this equation may be integrated to give:

$$\Omega = 2\,\pi\,k\,L\left(T_1 - T_2\right)/\ln\left(r_1/r_2\right)$$

Here T_1 is the inside temperature of the pipe wall and T_2 is the outside temperature. The difference in temperature ΔT across the wall of the pipe is then given by:

$$\Delta T = \Omega\ln\left(r_1/r_2\right)/2\pi\,k\,L$$

When the wall thickness is not small then the area through which the heat passes must be related to either the inside area or the outside area. Using the inside area A_1 gives the following equation:

$$\Delta T = \left(\Omega / A_1\right) r_1 \ln\left(r_1/r_2\right)/k$$

$$\Delta T = q\, r_1 \ln\left(r_1/r_2\right)/k \tag{4}$$

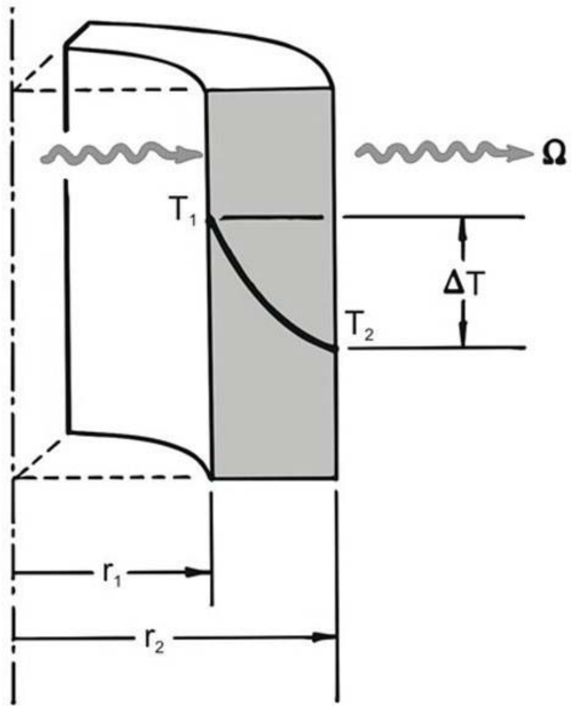

Figure 3: Heat conduction through a solid cylindrical wall

2.4. Contact Resistance

When two solid surfaces are in direct contact with one another there is additional resistance to heat transfer due to there not being continuous contact between the two materials on a microscopic scale. The tiny pockets formed by surface irregularities result in the heat conduction being less than that within either of the solid materials provided of course that the gas in the pockets has a lower thermal conductivity than either of the two solids. This can be expressed by the following equation where h_c is the contact heat transfer coefficient:

$$\Omega = h_c\ A\ (T_1 - T_2)$$

$$q = h_c (T_1 - T_2)$$

Here T_1 is the hot temperature and T_2 the cold temperature. The difference in temperature across the interface ΔT is then given by:

$$\Delta T = q/h_c \tag{5}$$

An application of this is in nuclear reactor fuel elements where the fuel pellets are in contact with the cladding surrounding the fuel.

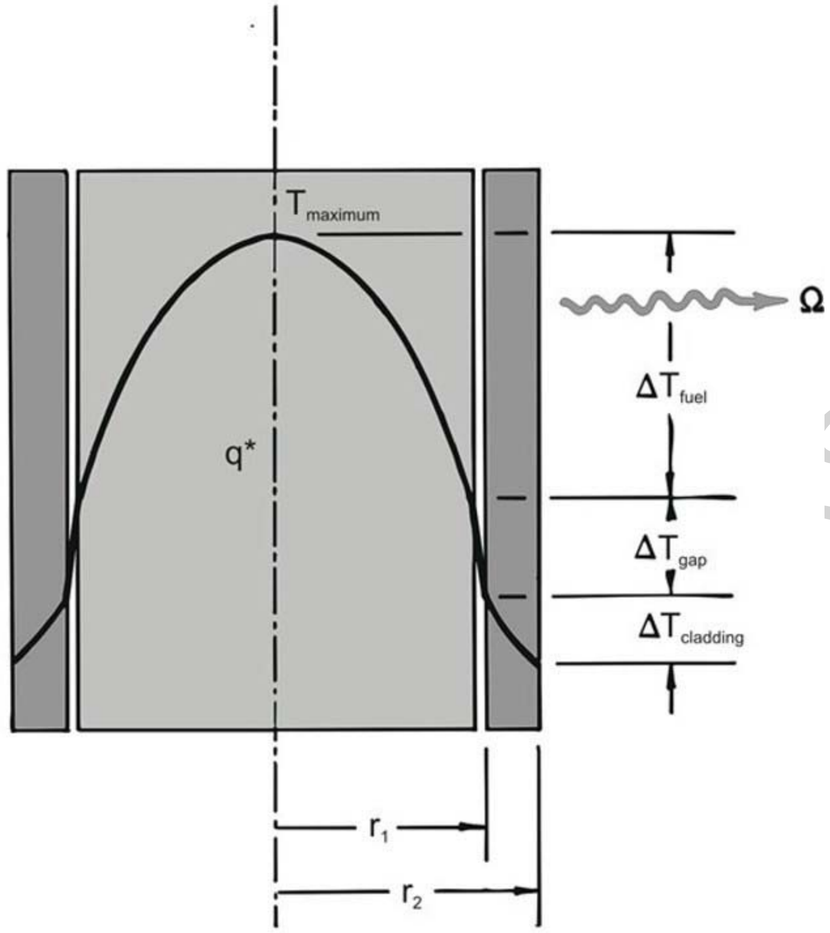

Figure 4: Contact resistance between two solids

2.5.Composite Heat Transfer Paths

When combining different modes of heat transfer or heat transfer across different elements there is an analogy with the flow of electricity or the flow of water.

Heat flow = Electrical current = Water flow
Temperature difference = Potential difference = Differential head
Thermal resistance = Electrical resistance = Frictional resistance

If the heat flow paths are in parallel the separate heat flows are added but if they are in series the separate temperature differences are added. When adding separate temperature differences due cognizance must be taken of a possible change in the area through which the heat passes. For heat transfer in a nuclear reactor the difference in temperature between the centre of the fuel pellet and the surface of the cladding is given as follows:

$$\Delta T_{\text{total}} = \Delta T_{\text{fuel}} + \Delta T_{\text{gap}} + \Delta T_{\text{cladding}}$$

$$\Delta T_{\text{total}} = qD/4k_{\text{fuel}} + q/h_{\text{c}} + qr_1 \ln(r_1/r_2)/k_{\text{cladding}}$$

If q in the third term had been referred to the outer radius r_2 it would not have been equal to the q in the other terms. It is better therefore to reference the volumetric heat generation rate in the equation and to reference the radius r_1

$$\Delta T_{\text{total}} = q^* r_1^2 \big/ 4k_{\text{fuel}} + q^* r_1^2 \big/ 2r_1 h_c + q^* r_1^2 \ln\left(r_1/r_2\right) \big/ 2k_{\text{cladding}} \quad (6)$$

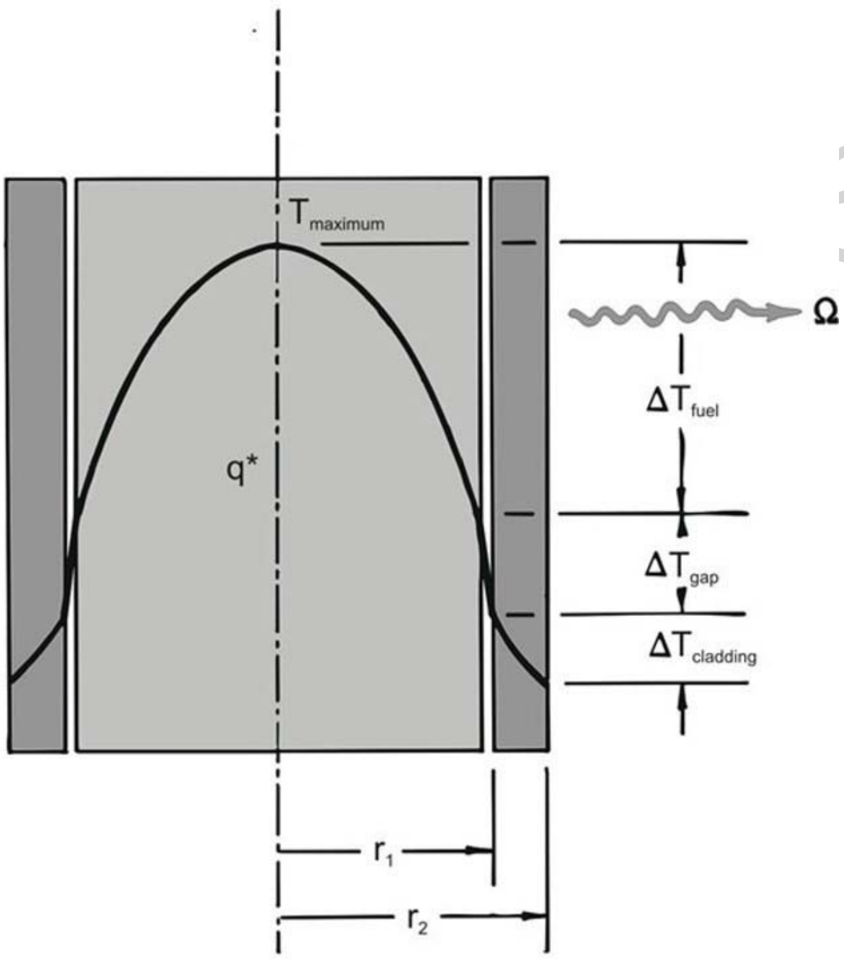

Figure 5: Heat conduction through a cylindrical fuel rod

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Biographical Sketch

Robin Chaplin obtained a B.Sc. and M.Sc. in mechanical engineering from University of Cape Town in 1965 and 1968 respectively. Between these two periods of study he spent two years gaining experience in the operation and maintenance of coal fired power plants in South Africa. He subsequently spent a further year gaining experience on research and prototype nuclear reactors in South Africa and the United Kingdom and obtained M.Sc. in nuclear engineering from Imperial College of London University in 1971. On returning and taking up a position in the head office of Eskom he spent some twelve years initially in project management and then as head of steam turbine specialists. During this period he was involved with the construction of Ruacana Hydro Power Station in Namibia and Koeberg Nuclear Power Station in South Africa being responsible for the underground mechanical equipment and civil structures and for the mechanical balance-of-plant equipment at the respective plants. Continuing his interests in power plant modeling and simulation he obtained a Ph.D. in mechanical engineering from Queen's University in Canada in 1986 and was subsequently appointed as Chair in Power Plant Engineering at the University of New Brunswick. Here he teaches thermodynamics and fluid mechanics and specialized courses in nuclear and power plant engineering in the Department of Chemical Engineering. An important function is involvement in the plant operator and shift supervisor training programs at Point Lepreau Nuclear Generating Station. This includes the development of material and the teaching of courses in both nuclear and non-nuclear aspects of the program.