Freestudy

FREESTUDY HEAT TRANSFER TUTORIAL 2 CONVECTION AND RADIATION This is the second tutorial in the series on basic heat transfer theory plus some elements of advanced theory. The tutorials are designed to bring the student to a level where he or she can solve problems ranging from basic level to dealing with practical heat exchangers. On completion of this tutorial the student should be able to do the following. - - Explain the use of the surface heat transfer coefficient. - Explain the use of the overall heat transfer coefficient. - Combine convection and conduction theory to solve problems involving flat, cylindrical and spherical surfaces. - Explain the basic theory behind radiated heat transfer. - Explain the affect of the emissivity and shape of the surface. - Calculate effective surface heat transfer coefficient. - (c) D. J. Dunn Explain natural and forced convection. Solve basic problems involving convection and radiation. 1 CONVECTION Convection is the study of heat transfer between a fluid and a solid body. Natural convection occurs when there is no forced flow of the fluid. Forced convection occurs when the fluid is forced to flow over the object. Consider a hot vertical surface placed in a cool fluid. The molecules in contact with the surface will receive heat transfer through the process of conduction. The fluid in contact with the surface will become hotter and less dense. If the fluid is a liquid that evaporates, the vapour will be less dense than the liquid. Because the fluid is less dense than the bulk fluid, it will rise and cool fluid will replace it. Natural convection currents are set up. Clearly the rate of heat transfer depends on the thermal conductivity of the fluid in contact with the surface and the volumetric expansion properties of the fluid. The flow of fluids over a surface is also a major topic in fluid mechanics and the work on boundary layers covered in other tutorials is important for a deep understanding of the topic.

When a fluid is in contact with a solid surface, the temperature of the fluid will vary in the region close to the surface. The diagram shows how the temperature might vary in a hot fluid in contact with a cooler solid surface. Clearly if we can make the temperature at the interface greater, the heat transfer will be increased. Consider a hot fluid flowing through a long pipe with heat transfer required into the wall of the pipe. The fluid in contact with the surface will reach the same temperature as the pipe at some point and further contact will not increase the transfer. The heat transfer will decrease with distance as shown. To improve the heat transfer, it is necessary to promote turbulent flow so that the fluid in the core is moved to the edges and comes in contact with the wall. BASIC CONVECTION LAW The heat transfer rate between a fluid and a solid surface by convection is usually given as Î¦ = -h A âˆ†Î¸ = h A (Î¸h - Î¸c) h is called the surface heat transfer coefficient and has units of W/m2 K. A is the surface area. The thermal resistance is R = 1/hA and this may be used for compound problems. The values of h depend on all the points raised previously and have largely been determined by empirical methods for specific conditions. For example, the value would be different for a flat vertical surface and a flat horizontal surface even if all other conditions are the same. Advanced studies will reveal formulae for finding h under a variety of conditions but at this stage we will simply use the values given. (c) D. J. Dunn 2 WORKED EXAMPLE No. 1 Calculate the heat transfer per square meter between a fluid with a bulk temperature of 66oC with a wall with a surface temperature of 25oC given h = 5 W/m2 K. SOLUTION Î¦ = h A (Î¸h - Î¸c) = 5 x 1 (66 — 25) = 205 W COMPOUND LAYERS We can now solve problems involving conduction and convection. Consider the case of the heat transfer from a hot fluid to cold fluid through a wall made from two layers. We have four thermal resistances. R1 = 1/h1A R2 = t1/k1A R3 = t2/k2A R4 = 1/h2A R = R1 + R2 + R3 + R4 Î¦ = (Î¸h - Î¸c)/R OVERALL HEAT TRANSFER COEFFICIENT First let’s look at the overall heat transfer coefficient for conduction and convection. Consider heat being convected to a surface, then conducted through a wall and convected to a fluid on the other side. There are three thermal resistances 1 1 x RA = RC = RB = h2 A kA h2 A In terms of the overall heat transfer coefficient Î¦ = U A âˆ†Î¸ In terms of thermal resistance Î¦ = âˆ†Î¸ A âˆ†Î¸ = (R A + R B + R C) âŽ› 1 x 1 âŽž âŽœ++ âŽŸ âŽœh k h2 âŽŸ 1 âŽ� âŽ A âˆ†Î¸ = U A âˆ†Î¸ âŽ›1 x 1âŽž âŽœ++ âŽŸ âŽœh âŽŸ âŽ� 1 k h2 âŽ 11 1x =+ + It is apparent that U h1 h 2 k This maybe extended to any number of layers in series. Equate and (c) D. J. Dunn 3 WORKED EXAMPLE No. 2 Calculate the heat transfer per square meter between a fluid with a bulk temperature of 160oC and another with a bulk temperature of 15oC with a wall between them made of two layers A and B both 50 mm thick. The surface heat transfer coefficient for the hot fluid is 5 W/m2 K and for the cold fluid 3 W/m2 K. The thermal conductivity of layer A is 20 W/m K and for B it is 0. 5 W/m K. Also calculate the overall heat transfer coefficient. SOLUTION For the hot fluid to the wall R1 = 1/h1A = 1/(5 x 1) = 0. 2 K/W For Layer A R2 = t1/ k1A = 0. 05/(20 x 1) = 0. 0025 K/W For Layer B R3 = t2/ k2A = 0. 05/(0. 5 x 1) = 0. 1 K/W For the wall to the cold fluid R4 = 1/h2A = 1/(3 x 1) = 0. 333 K/W The total thermal resistance is R = 0. 2 + 0. 0025 + 0. 1+ 0. 333 = 0. 6355 K/W Î¦ = (Î¸h - Î¸c)/R = (160 — 15)/ 0. 6355 = 228. 2 W Î¦ = U A (Î¸h - Î¸c) U = 228. 2/(1 x 145) = 1. 573 W/m2 K or 1 1 x1 x 2 1 1 0. 05 0. 05 1 =++ + =+ + + = 0. 636 U = 1/0. 636 = 1. 573 W/m2 K U h1 k1 k 2 h 2 5 20 0. 5 3 SELF ASSESSMENT EXERCISE No. 1 1. Calculate the heat transfer through a steel plate with water on one side at 90oC and air on the other at 15oC. The plate has an area of 1. 5 m2 and it is 20 mm thick. The thermal conductivity is 60 W/m K. The surface heat transfer coefficients for the air and water respectively are 0. 006 W/m2 K and 0. 08 W/m2 K. Calculate the heat loss and the overall heat transfer coefficient. (Answer 0. 628 W and 5. 581 x 10-3 W/m2 K) 2. A wall with an area of 25 m2 is made up of four layers. On the inside is plaster 15 mm thick, then there is brick 100 mm thick, then insulation 60 mm thick and finally brick 100 mm thick. The thermal conductivity of plaster is 0. 1 W/m K. The thermal conductivity brick is 0. 6 W/m K The thermal conductivity the insulation is is 0. 08 W/m K The one side of the wall is in contact with air at 22oC and the other with air at -5oC. The surface heat transfer coefficient for both surfaces is 0. 006 W/m2 K. Calculate the heat loss and the overall heat transfer coefficient. (Answer 1. 79 W and 3 x 10-3 W/m2 K) 3. A steam pipe 8m long has an external diameter of 100 mm and it is covered by lagging 50 mm thick. The pipe contains steam at 198 oC and the temperature of the atmosphere surrounding the pipe is 18oC. The thermal conductivity of the lagging is 0. 15 W/m K. The surface heat transfer coefficient is 10 W/m2 K. Assuming the pipe has the same uniform temperature as the steam, calculate the heat loss and the surface temperature of the lagging. (Answer 6. 1 W and 18. 04oC) 4. A spherical tank 2 m diameter contains liquefied fuel gas. It is covered in insulation 120 mm thick with a thermal conductivity of 0. 025 W/m K. The surface heat transfer coefficient between the lagging and the surrounding air is 30 W/m2 K. The air is at 25oC and the liquid is -125oC. Assume the inner surface temperature is the same as the liquid. Calculate the heat transfer rate required to keep the liquid at a constant temperature and surface temperature of the insulation. (Answer 437 W and 24. 1oC) (c) D. J. Dunn 4 RADIATION A hot body radiates energy in the form of electromagnetic radiation. It is found that the energy radiated depends upon the absolute temperature to the power of 4. A BLACK BODY is one that can absorb all the radiated energy falling on it. A black body will radiate energy according to the law Î¦ = Ïƒ A T 4 Ïƒ is a constant called the Stefan-Boltzmann constant and has a value of 56. 7 x 10-9 W/m2 k4 If two identical black bodies at temperatures T1 and T2 radiate heat to each other, the net heat 4 transfer is Î¦ = ÏƒA(T14 âˆ’ T2) For bodies other than black, the heat radiated depends upon the type of surface and we introduce a property Îµ called the emissivity to correct the calculation. 4 Î¦ = Îµ Ïƒ A (T14 âˆ’ T2) For two identical bodies with different emissivities Îµ1 and Îµ2 it can be shown that 4 Ïƒ A (T14 âˆ’ T2) Î¦= 1/Îµ1 + 1/Îµ 2 These equations take no account of the shape and orientation of the bodies with respect to each other and should be used with caution. TYPICAL VALUES OF Îµ These values depend on the temperature and are given as a rough guide only. Material Îµ Material Îµ Aluminium Polished 0. 04 Aluminium Oxidised 0. 12 Copper Polished 0. 02 Copper Oxidised 0. 6 Tungsten Polished 0. 02 Steel Polished 0. 1 Steel Oxidised 0. 8 Brick White Paint 0. 9 Black Paint 0. 97 0. 9 Tungsten Oxidised 0. 06 WORKED EXAMPLE No. 3 Two identical bodies radiate heat to each other. One body is at 30oC and the other at 250 oC. The emissivity of both is 0. 7. Calculate the net heat transfer per square meter. SOLUTION ( ) 4 Î¦ = Îµ Ïƒ A (T14 âˆ’ T2) = 0. 7 x 56. 7 x 10 -9 x 1 x 5234 âˆ’ 3034 = 2635 W (c) D. J. Dunn 5 EFFECTIVE RADIATION SURFACE HEAT TRANSFER COEFFICIENT Sometimes we wish to calculate the radiated heat by a formula similar to the convection formula so that Î¦r = hr A âˆ†T hr is the radiated surface heat transfer coefficient. (Note â̂†T â‰¡ â̂†Î¸) Equate Î¦ = 4 4 2 Ïƒ A (T14 â̂’ T2) Ïƒ A (T14 â̂’ T2) Ïƒ (T1 + T2)(T12 + T2) = = h r A(T1 â̂’ T2) h r = (1/Îµ1 + 1/Îµ 2)A(T1 â̂’ T2) (1/Îµ1 + 1/Îµ 2) 1/Îµ1 + 1/Îµ 2 SHAPE FACTOR Consider two small black areas radiating energy to each other as shown. The normal to the area makes an angle Ï† with the line joining them. It can be shown that the net heat transfer is: Ïƒ cos Ï†1 cos Ï† 2 dA1 dA 2 4 dÎ¦ = T2 â̂’ T14 2 Ï€x Solving for complete areas involves two integrations. Ïƒ cos Ï†1 cos Ï†2 dA The shape factor is given by F = â̂« This has one value when solved with respect A Ï€ x2 to area 1 and another when solved with respect to area 2. Ïƒ cos Ï†1 cos Ï†2 dA 2 F(1 - 2) = â̂« is the factor for area 1 with respect to area 2. A Ï€ x2 Ïƒ cos Ï†1 cos Ï†2 dA1 F(2 - 1) = â̂« is the factor for area 2 with respect to area 1. A Ï€ x2 4 4 The net heat transfer from between both areas is Î¦ = Ïƒ T2 â̂’ T14 A1 F(1 â̂’ 2) = Ïƒ T2 â̂’ T14 A 2 F(2 â̂’ 1) It follows that A1 F(1 â̂’ 2) = A 2 F(2 â̂’ 1) ( ) ( ) (When we have two surfaces with different emissivity it can be shown that: Î¦= ( ) 4 Ïƒ T14 â̂’ T2 âŽ« âŽ§ (1 â̂’ Îµ1) âŽ« âŽ§ (1 â̂’ Îµ 2)âŽ« âŽ§ 1 âŽ¬ âŽ¬+âŽ¨ âŽ¬+âŽ¨ âŽ¨ âŽ© Îµ1A1 âŽ âŽ© Îµ 2 A 2 âŽ âŽ© A1F(1 â̂’ 2) âŽ TOTALLY ENCLOSED BODY Consider a body totally surrounded by another body. Heat is exchanged between the two. It can be shown that the shape factor is 1. 0 so the net heat 4 transfer is Î¦ = Îµ Ïƒ A (T14 â̂’ T2) A is the envelope area of the enclosed body. For difficult shapes like that shown, it should be regarded as the area that would be obtained by stretching an elastic membrane over it. (c) D. J. Dunn 6) WORKED EXAMPLE No. 4 A radiator may be treated as a black body with a true surface area of 12 m2 and an envelope area of 5 m2. It has a surface temperature of 55oC and is situated in a dark room at 15oC. The surface heat transfer coefficient is 4. 5 W/m2 K. Calculate the radiated heat transfer and the convected heat transfer rate. Calculate the radiated surface heat transfer coefficient and obtain the same answers using it. SOLUTION ( ) 4 Radiated heat - Î¦ = Îµ Ïƒ A e (T14 âˆ’ T2) = 1 x 56. 7 x 10 -9 x 5 x 328 4 âˆ’ 288 4 = 1331 W Convected heat transfer Total Î¦ = hA (T1 âˆ’ T2) = 4. 5 x 12 x (328 âˆ’ 288) = 2160W 1331 + 2160 = 3491 W Effective radiated surface heat transfer coefficient (2 h r = Îµ Ïƒ (T1 + T2)(T12 + T2) = 1 x 56. 7 x 10-9 x (328 + 288) 3282 + 2882 hr = 6. 65 W/m2 k4) Î¦ = hr Ae âˆ†Î¸ + h A âˆ†Î¸ = (6. 65 x 5 x 40) + (4. 5 x 12 x 40) = 1331 + 2160 = 3491 W SELF ASSESSMENT EXERCISE No. 2 1. A space vehicle is in a totally dark vacuum at absolute zero. The envelope area is 20 m2. The heat loss into space must not exceed 200W. The emissivity of the surface is 0. 2. Calculate the surface temperature of the vehicle. (257. 7 K) 2. A radiator may be treated as a black body with a true surface area of 6 m2 and an envelope area of 4 m2. It has a surface temperature of 40oC and is situated in a dark room at 20oC. The surface heat transfer coefficient is 4 W/m2 K. Calculate the radiated heat transfer and the convected heat transfer rate. Calculate the radiated surface heat transfer coefficient and obtain the same answers using it. (985 W and 6. 32 W/m2 k4) (c) D. J. Dunn 7