CHAPTER 6
RESULTS AND DISCUSSION

The results of the investigations are presented in two sections. The results of the analysis are presented in the first section. The second section deals with the experimental data and related discussion.

6.1 Results of the Analysis

As stated earlier (in Chapter 5), the experiments were conducted for particle sizes of 6-0 mm, 5-0 mm, 4-0 mm and 3-0 mm. To correlate the experimental values with the heat transfer model discussed earlier (in Chapter 3), the salient bed parameters and heat transfer coefficients were calculated analytically. As the bed was made up of burning coal particles with widely varying particle sizes, the mean diameters of the particles in the bed were found by sieve analysis.

Typical analytical results for a tube of 60 mm outer diameter, mean particle size of 0.82 mm (bed particle size of 6-0 mm), bed temperature of 800°C and fluidizing velocity of 1.0 m/s are presented as representative values. Further, the tube locations at 30°, 90° and 170° measured around the circumference from the top of the tube are chosen as representative locations for the defluidized, fluidized and stagnation regions respectively. The results obtained in the analysis are shown in Figures 6.1 to 6.27.
6.1.1 Heat transfer in the fluidized region

The variation of the temperature of the emulsion packet along its length at the end of the average residence time, that is when it is about to rejoin the core of the bed over the tube circumference is shown in Figure 6.1, for the fluidized and stagnation regions viz. 70 to 180°. It can be seen that the temperature level of the emulsion packet increases in the locations along the tube circumference in the flow direction. This increase can be attributed to the twin causes of decrease in the bed voidage and increased gas velocity in the vicinity of the tube along its circumference. As reported by Rooney and Harrison [32] there is a reduction in the local voidage by about 15 percent as the position changes from 170° to 75° location causing a consequential increase in the emulsion packet density. The increase in velocity along the circumference [38] decreases the residence time of the emulsion packet at the boundary layer. Consequent to these two effects the rate of cooling of the emulsion packet at the boundary layer is decreased.

The variation of the temperature of a typical emulsion packet along its length in the fluidized region at the end of the average residence time with fluidizing velocity is shown in Figure 6.2. In this region, a decrease in the temperature of the packet is observed when the fluidizing velocity is increased. This may be attributed to the
TEMPERATURE (DIMENSIONLESS)

DISTANCE ALONG EMULSION, \( d_p \)

\( \phi = 75^\circ \)

90

105

120

135

150

170

TUBE OUTER DIAMETER : 60 mm
PARTICLE SIZE : 6-0 mm
BED TEMPERATURE : 800 °C
FLUIDIZING VELOCITY : 1.0 m/s

FIGURE 6.1 TEMPERATURE OF EMULSION PACKETS ALONG THE CIRCUMFERENCE OF THE TUBE IN THE FLUIDIZED AND STAGNATION REGIONS
FIGURE 6.2 TEMPERATURE OF EMULSION PACKET WITH FLUIDIZING VELOCITY IN THE FLUIDIZED REGION

TUBE OUTER DIAMETER: 60mm
PARTICLE SIZE: 6-0 mm
BED TEMPERATURE: 800°C
LOCATION: FLUIDIZED REGION
opposing influence of the increase in velocity on the bed voidage and residence time of the emulsion packets at the interface. While the particle concentration decreases at higher velocities resulting in increased rate of cooling of the emulsion packet, the increase in velocity decreases the residence time of the emulsion packet at the boundary layer reducing the time of cooling.

In all these cases, it can also be seen that the cooling of the emulsion packet is limited to a distance of 1.5 dp, thus proving the validity of the boundary condition, $T = T_b$ at $r = r_0$ assumed in the analysis. This is also in close agreement with the findings of Ilchenko et.al [41] who, while studying the degree of cooling of particles on individual water cooled tubes, have found that cooling extended only to a distance of one particle diameter.

The variation of the instantaneous specific heat flux with residence time of the emulsion packet at the surface of the boundary layer in the fluidized region is shown in Figure 6.3. It can be seen that the bubble phase heat flux is independent of time whereas the emulsion phase heat flux is decreasing with the time of contact of the emulsion packet. The decrease in the emulsion phase heat flux may be due to the cooling of the emulsion packet with time. Further, an increase in the bubble and emulsion phase heat fluxes are observed with increase in fluidizing velocity. The increase in the bubble phase heat flux may
Figure 6.3. Instantaneous specific heat flux with residence time in the fluidized region.
be due to the increase in the volume of the bubble phase with velocity. The increase in the emulsion phase heat flux may be because of the decrease in boundary layer thickness at higher velocities [39]. The decrease in the boundary layer thickness increases the rate of heat transfer by emulsion phase and cools the emulsion packet with increase in velocity as noticed in Figure 6.2.

The variation of the heat transfer coefficients with fluidizing velocity in the fluidized region of the tube for bed temperatures of 700, 800 and 900°C are shown in Figures 6.4 and 6.5. An increase in the total and radiative heat transfer coefficients are observed with increase in velocity. A similar trend is also observed for the emulsion and bubble phase heat transfer coefficients. The increase in the bubble phase heat transfer may be due to the increase in the area of the tube surface contacted by the bubbles, as the velocity increases. The increase in the emulsion phase heat transfer may be attributed to the reduction in the boundary layer thickness and the decrease in the residence time of the emulsion packet with increase in velocity. The increase in the total and radiative heat transfer coefficients are due to the increase in the bubble and emulsion phase heat transfer coefficients.

The variation of heat transfer coefficients with bed temperature for a mean particle diameter of 0.82 mm (6-0 mm)
RADIATIVE H.T.C.
TOTAL H.T.C.

TUBE OUTER DIAMETER : 6.0 mm
PARTICLE SIZE : 0.82 mm
LOCATION : FLUIDIZED REGION

FIGURE 6.4. VARIATION OF HEAT TRANSFER COEFFICIENTS WITH FLUIDIZING VELOCITY IN THE FLUIDIZED REGION

LOCAL HEAT TRANSFER COEFFICIENT, wcm²/°C

FLUIDIZING VELOCITY, m/s
FIGURE 6.5: VARIATION OF HEAT TRANSFER COEFFICIENTS WITH FLUIDIZING VELOCITY IN THE FLUIDIZED REGION
in the fluidized region of the tube are shown in Figures 6.6 and 6.7. It can be noticed that the heat transfer coefficients increase with increase in bed temperature. The increase in the radiative and bubble phase heat transfer coefficients may be due to the increase in bubble phase volume with increase in temperature. The increase in the emulsion phase heat transfer may be attributed to the increase in the thermophysical properties and decrease in the boundary layer thickness with increase in temperature [39]. The increase in the bubble and emulsion phase heat transfer thus contribute for the increase in the total heat transfer coefficient.

The variation of heat transfer coefficients with particles size for a bed temperature of 800°C in the fluidized region of the tube are shown in Figures 6.8 and 6.9. It is observed that the total and emulsion phase heat transfer coefficients decrease with increase in particle size. This may be due to the decrease in the replacement rate of the emulsion packet with increase in particle size at the fluidized region. Further, it is observed that the bubble phase and radiative coefficients marginally decrease with increase in particle size.

The variation of heat transfer coefficients with tube size for a mean particle size of 0.82 mm at a bed temperature of 800°C are shown in Figures 6.10 and 6.11.
FIGURE 6.6. VARIATION OF HEAT TRANSFER COEFFICIENTS WITH BED TEMPERATURE IN THE FLUIDIZED REGION.
FIGURE 6.7: VARIATION OF HEAT TRANSFER COEFFICIENTS WITH BED TEMPERATURE IN THE FLUIDIZED REGION

TUBE OUTER DIAMETER: 60 mm
PARTICLE SIZE: 0.8 mm
LOCATION: FLUIDIZED REGION
--- BUBBLE PHASE H.T.C.
--- EMULSION PHASE H.T.C.
Figure 6.6: Variation of heat transfer coefficients with particle size in the fluidized region.
FIGURE 6.9. VARIATION OF HEAT TRANSFER COEFFICIENTS WITH PARTICLE SIZE IN THE FLUIDIZED REGION
FIGURE 6.10. VARIATION OF HEAT TRANSFER COEFFICIENTS WITH TUBE SIZE IN THE FLUIDIZED REGION.
FIGURE 6.11. VARIATION OF HEAT TRANSFER COEFFICIENTS WITH TUBE SIZE IN THE FLUIDIZED REGION
It is observed that the total and emulsion phase heat transfer coefficients decrease with increase in tube diameter. This may be due to the decrease in boundary layer thickness, when the tube diameter is decreased. Further, it is found that there is no change in the bubble phase heat transfer with tube size. Moreover, the radiative coefficient increases marginally with increase in tube size.

6.1.2 Heat transfer in the stagnation region

The variation of the temperature of a typical emulsion packet along its length in the stagnation region at the end of the average residence time is shown in Figure 6.12. It is observed that an increase in fluidizing velocity increases the temperature level of the emulsion packet up to the velocity of 1 m/s and after that it decreases with further increase in fluidizing velocity. The increase in the temperature level of the emulsion packet may be attributed to the decrease in the residence time of the emulsion packet at the boundary layer with increase in velocity. With further increase in velocity, the opposing influence of the increase in voidage causes the emulsion packet to be at a decreased temperature level. Further, it is seen that, at this location the change in temperature level with fluidizing velocity is not very significant. This may be due to the interplay of the replacement rate and the voidage of the emulsion packet. Moreover, it is observed that at the stagnation region,
FIGURE 6.12 TEMPERATURE OF EMULSION PACKET WITH FLUIDIZING VELOCITY IN THE STAGNATION REGION
the temperature level of the emulsion packet is lower than that at the fluidized region. This may be attributed to the lower velocity and higher voidage of the emulsion packet at the stagnation region, compared to that at the fluidized region [32, 38].

The variation of the instantaneous specific heat flux with residence time of the emulsion packet at the surface of the boundary layer in the stagnation region is shown in Figure 6.13. It is observed that the bubble phase heat flux is independent of time, whereas the emulsion phase heat flux is decreasing with time of contact of the emulsion packet. Further, the decrease in the emulsion phase heat flux is faster than that at the fluidized region. This phenomenon may be because of the fast cooling of the emulsion packet at the stagnation region, where the voidage is higher and the velocity is lower, compared to that at the fluidized region. Further, it is found that the bubble phase heat flux increases with increase in fluidizing velocity whereas the emulsion phase heat flux decreases. The increase in the bubble phase heat flux may be due to the increase in bubble phase volume with velocity. The decrease in the emulsion phase heat flux may be attributed to the decrease in the area of the tube in contact with the emulsion phase and the increase in the replacement rate of the emulsion packet with increase in velocity. Though the increase in the replacement rate of the emulsion packet increases the temperature level of the emulsion packet upto
Figure 6.13. Instantaneous specific heat flux with residence time in the stagnation region.
certain velocity as noticed in Figure 6.12, the decrease in the area of the tube contacted by emulsion phase decreases the emulsion phase heat transfer. With further increase in velocity the opposing influence of increase in voidage predominates and cools the emulsion packet as is also seen in Figure 6.12. This decrease in the temperature of the emulsion packet and the decrease in the area of the tube in contact with the emulsion phase with increase in fluidizing velocity decreases the emulsion phase heat flux.

The variation of heat transfer coefficients with fluidizing velocity at the stagnation region of the tube are shown in Figures 6.14 and 6.15. It is seen that the total heat transfer coefficient decreases with increase in velocity. A similar trend is also observed for the emulsion phase heat transfer coefficient. However, the bubble phase and radiative heat transfer coefficients do not exhibit such a trend and their values increase with velocity. The decrease in the emulsion phase heat transfer may be due to the cooling of the emulsion packet with increase in voidage with velocity in this region. The increase in the bubble phase heat transfer may be because of the increase in the area of the tube exposed to bubbles when the velocity increases. Further, the increase in the radiative coefficient is due to the increase in the bubble phase heat transfer and the decrease in the total coefficient is due to the decrease in the emulsion phase heat transfer.
Figure 6.14. Variation of Local Heat Transfer Coefficients with Fluidizing Velocity in the Stagnation Region

- Tube outer diameter: 60 mm
- Particle size: 0.82 mm
- Location: Stagnation Region

**Tubes**
- Total H.T.C.
- Radiative H.T.C.

**Graph Details**
- X-axis: Fluidizing Velocity (m/s)
- Y-axis: Local Heat Transfer Coefficient (W/m²K)
- Temperature Levels: 700°C, 800°C, 900°C

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Additional Notes:
- TOSS Outer Diameter: 60 mm
- Location: Stagnation Region
- Particle Size: 0.82 mm
Figure 6.15: Variations of heat transfer coefficients with fluidizing velocity in the stagnation region.

- Tube outer diameter: 60 mm
- Particle size: 0.82 mm
- Location: Stagnation region

- Bubble phase H.T.C.
- Emulsion phase H.T.C.

Variables:
- Fluidizing velocity $u_f$
- Temperature $T_0$
- Heat transfer coefficients (watts/m²°C)
The variation of heat transfer coefficients with bed temperature are shown in Figures 6.16 and 6.17 for the stagnation region. It is seen that the heat transfer coefficients increase with increase in bed temperature. The increase in the emulsion phase and the total heat transfer coefficients may be due to the change in the thermophysical properties of the bed and the increase in the temperature of the emulsion packet. The increase in the bubble phase and radiative heat transfer may be attributed to the increase in the area of the tube exposed for the bubble phase heat transfer. Further, it is seen that at this region, the increase in the heat transfer coefficients are lower than that at the fluidized region as seen in Figure 6.6 with increase in bed temperature. This may be because of the higher voidage and lower velocity at the stagnation region.

The variation of heat transfer coefficients with particle size in the stagnation region for a bed temperature of 800°C and a tube outer diameter of 60 mm are shown in Figures 6.18 and 6.19. It is observed that the emulsion phase and total heat transfer coefficients decrease with increase in particle size. This may be due to the increase in the residence time of the emulsion packet at the boundary layer. Further, it is observed that the bubble phase and radiative heat transfer coefficients decrease with increase in particle size.
Figure 6.16. Variation of heat transfer coefficients with bed temperature in the stagnation region.
Figure 6.17. Variation of heat transfer coefficients with bed temperature in the stagnation region.
PARTICLE SIZE

FIGURE 6.18. VARIATION OF HEAT TRANSFER COEFFICIENTS WITH PARTICLE SIZE IN THE STAGNATION REGION
Figure 6.19: Variation of heat transfer coefficients with particle size in the stagnation region.
The variation of heat transfer coefficients with tube size at the stagnation region of the tube for a bed temperature of 800°C and a mean particle diameter of 0.82 mm are shown in Figures 6.20 and 6.21. It is observed that there is no change in the total and emulsion phase heat transfer coefficients as the tube diameter is increased. Further, a similar trend is observed for the bubble phase and radiative coefficients.

6.1.3 Heat transfer in the defluidized region

The variation of the temperature of the cap of the defluidized particles along its radial length over the circumference of the tube in the defluidized region is shown in Figure 6.22. It can be seen that the temperature gradient of the defluidized particles and the temperature at the gas film increases along the circumference from the top of the tube. This may be due to the decrease in the radial distance of the defluidized cap along the circumference from the top of the tube. It may be explained further that a decrease in the radial distance of the cap reduces the resistance for heat transfer to the tube surface from the core of the bed.

The variation of the temperature of the defluidized particles along its length with fluidizing velocity at the defluidized region is shown in Figure 6.23. It is observed that the temperature level of the defluidized
Figure 6.20. Variation of heat transfer coefficients with tube size in the stagnation region.
Figure 6.21. Variation of heat transfer coefficients with tube size in the stagnation region.
FIGURE 6.22 TEMPERATURE OF THE FLUIDIZED CAP ALONG THE RADIAL DISTANCE
FIGURE 6.23 TEMPERATURE OF DEFLUIDIZED CAP WITH FLUIDIZING VELOCITY
particles increases with increase in fluidizing velocity. This may be because of the increase in the effective thermal conductivity of the defluidized particles with increase in fluidizing velocity.

The variation of heat transfer coefficients in the defluidized region with fluidizing velocity for a tube diameter of 60 mm and a mean particle diameter of 0.82 mm are shown in Figure 6.24. It is seen that the radiative and total heat transfer coefficients are increasing with increase in fluidizing velocity. This may be due to the increase in the effective thermal conductivities of the defluidized particles and the gas film near the tube surface. The increase in the effective thermal conductivities may be because of the increase in heat transfer by turbulent diffusion as the velocity of the gas increases.

The variation of the heat transfer coefficients with bed temperature for a tube size of 60 mm outer diameter and a mean particle diameter of 0.82 mm in the defluidized region are shown in Figure 6.25. It is observed that the radiative and the total heat transfer coefficients are increasing with increase in bed temperature. This may be because of the increase in the effective thermal conductivities of the defluidized particles and the gas film near the tube surface at higher temperatures.
FIGURE 6.24. VARIATION OF HEAT TRANSFER COEFFICIENTS WITH FLUIDIZING VELOCITY IN THE DEFLUIDIZED REGION

TUBE OUTER DIAMETER : 60 mm
PARTICLE SIZE : 0.82 mm
LOCATION : DEFLUIDIZED REGION
--- RADIATIVE H.T.C.
--- TOTAL H.T.C.

FLUIDIZING VELOCITY, m/s

LOCAL HEAT TRANSFER COEFFICIENT, w/m²K

Tₜ = 900°C
800°C
700°C

FIGURE 6.24, VARIATION OF HEAT TRANSFER COEFFICIENTS WITH FLUIDIZING VELOCITY IN THE DEFLUIDIZED REGION
FIGURE 6.25. VARIATION OF HEAT TRANSFER COEFFICIENTS WITH BED TEMPERATURE IN THE DEFLUIDIZED REGION
The variation of heat transfer coefficients with particle size for a bed temperature of 800°C and tube, outer diameter of 60 mm are shown in Figure 6.26. It is seen that the radiative coefficient increases with increase in particle size whereas the total coefficient decreases with increase in particle size. The increase in the radiative coefficient may be due to the increase in interface temperature with particle size. The interface temperature increases with increase in the effective thermal conductivity of the defluidized particles. The increase in the effective thermal conductivity of the defluidised particles may be due to the increase in heat transfer by turbulent diffusion when the particle size increases. The decrease in the total heat transfer coefficient may be due to the increase in gas film thickness, with increase in particle size which decreases the conductive heat transfer through the gas film.

The variation of heat transfer coefficients in the defluidized region with tube size for a mean particle diameter of 0.82 mm and a bed temperature of 800°C are shown in Figure 6.27. It is observed that the radiative and total heat transfer coefficients decrease with increase in tube outer diameter. This may be attributed to the increase in the size of the defluidized particles cap with increase in tube diameter. The increase in cap size decreases the interface temperature and in turn decrease the total and radiative heat transfer coefficients.
FIGURE 6.26 VARIATION OF HEAT TRANSFER COEFFICIENTS WITH PARTICLE SIZE IN THE DEMULSION REGION

TUBE OUTER DIAMETER
BED TEMPERATURE: 900°C
LOCATION: DEFUZED REGION
PARTICLE SIZE: 9 mm
LOCAL HEAT TRANSFER COEFFICIENTS: \( \nu \text{m}^2/\text{W} \)
FIGURE 6.27 VARIATION OF HEAT TRANSFER COEFFICIENTS WITH TUBE SIZE IN THE DEFLUIDIZED REGION.
6.2 Experimental Results

The experiments were conducted for particle sizes of 6-0, 5-0, 4-0 and 3-0 mm, bed temperatures of 700, 750, 800, 850 and 900°C, tube sizes of 32, 42, 50 and 60 mm outer diameter and at fluidizing velocities of 0.6 to 1.4 m/s. The typical experimental results obtained for a tube size of 60 mm outer diameter, particle size of 6-0 mm, bed temperature of 800°C and a fluidizing velocity of 1.0 m/s are presented as the representative values. The local heat transfer data obtained are presented in Figures 6.28 to 6.31 and in Appendix J.

6.2.1 Effect of fluidizing velocity

The experimentally observed local values of radiative and total heat transfer coefficients with fluidizing velocity are shown in Figures 6.28 to 6.31 for a bed particle size of 6-0 mm and bed temperatures of 700 and 900°C. It is found that the maximum values of the total and radiative heat transfer coefficients occur at the lower portion of the tube for the lowest fluidizing velocity of 0.8 m/s. As the fluidizing velocity is increased, an increase in the total heat transfer coefficient is observed along most parts of the tube perimeter i.e., the defluidized region at the top and the fluidized region at the sides. But in the lower portion of the tube extending from 150 to 180° viz., the lower portion of the fluidized region and the stagnation region the coefficient
Figure 6.28 Variation of local total and radiative heat transfer coefficients with fluidizing velocity.
Figure 6.29 Variation of Local Total and Radiative Heat Transfer Coefficients with Fluidizing Velocity.
Figure 6.30 Variation of local total and radiative heat transfer coefficients with fluidizing velocity (experimental)
FIGURE 6.31 VARIATION OF LOCAL TOTAL AND RADIATIVE HEAT TRANSFER COEFFICIENTS WITH FLUIDIZING VELOCITY (EXPERIMENTAL)
decreases with increase in velocity. Further, at the defluidized region and the upper portion of the fluidized region the quantum of increase in the coefficient is particularly higher. Moreover, it is observed that the radiative coefficient increases all along the tube circumference. The increase in the heat transfer coefficients at the fluidized region of the tube may be attributed to the decrease in the residence time of the emulsion packet and the decrease in the boundary layer thickness with increase in velocity. A higher increase in the coefficients at the upper portion of the fluidized region may be caused by the rising bubbles which detach near the sides of the tube and increase the circulation of the particles[34]. The increase in the particle replacement rate and circulation reduces the cooling of the emulsion packet and increases the heat transfer coefficients.

The increase in the heat transfer coefficients at the defluidized region of the tube may be due to the increase in the effective thermal conductivity and mobility of the defluidized particles. Further, a reduction in the size and turnover time of the defluidized cap with increase in velocity [33] may also increase the heat transfer coefficients.

The decrease in the total coefficient at the stagnation region of the tube can be attributed to the
increase in voidage at higher velocities. This increase in voidage naturally causes an increase in the radiative coefficient.

Further, at high temperature the increase in fluidizing velocity shows a significant improvement in the heat transfer coefficients at the fluidized and defluidized regions of the tube. This may be due to the fact that, when the bed is operating at higher temperatures, the bubble size decreases, but its number increases [42]. This increase in number of bubbles may push more particles and burst at the sides of the tube, resulting in an increase in the circulation of the particles. In addition, the boundary layer thickness at the tube surface decreases with increase in velocity and temperature. The combined effect of these factors result in the observed increase in the heat transfer coefficients at the fluidized and defluidized regions of the tube.

The circumferential variation of the ratio of the total and radiative heat transfer coefficients to their mean values for a bed temperature of 800°C and a particle size of 6-0 mm are shown in Figures 6.32 and 6.33 respectively. It is observed that the deviation of the total heat transfer coefficient from its mean value decreases from 62 to 27 percent and the radiative coefficient from 70 to 23 percent when the fluidizing velocity is increased
BOTTOM TUBE OUTER DIAMETER  60 mm
PARTICLE SIZE  6.0 mm
BED TEMPERATURE  800°C
FLUIDIZING VELOCITY  

0.8 m/s
1.0 m/s
1.2 m/s
1.4 m/s

FIGURE 6.32 VARIATION OF LOCAL TOTAL HEAT TRANSFER COEFFICIENT (DIMENSIONLESS) WITH FLUIDIZING VELOCITY (EXPERIMENTAL)
PARTICLE SIZE : 6-0 mm
BED TEMPERATURE : 800 °C
FLUIDIZING VELOCITY :
- - - - - - 0.8 m/s
- - - - - - - 1.0 m/s
- - - - - - - 1.2 m/s
- - - - - - - 1.4 m/s

FIGURE 6.33 VARIATION OF LOCAL RADIATIVE HEAT TRANSFER COEFFICIENT WITH FLUIDIZING VELOCITY (EXPERIMENTAL)
from 0.8 to 1.4 m/s. It is further observed that the increase in the velocity, shift the locations of the maximum heat transfer coefficients to the sides of the tube. The reduction in the local deviation of the heat transfer coefficients may be due to the result of the increase in heat transfer coefficients at the defluidized region of the tube, when the fluidizing velocity is increased. The shifting of the maximum heat transfer coefficients to the sides of the tube may be the result of the increased circulation of the particles caused by the bursting of the rising bubbles at the sides.

The local variation of the conductive heat transfer coefficient with fluidizing velocity for a particle size of 6-0 mm and bed temperatures of 700 and 900°C are shown in Figures 6.34 and 6.35. It is observed that the conductive coefficient increases in the defluidized and fluidized regions of the tube. The increase in the coefficient at the fluidized region of the tube may be attributed to a decrease in the boundary layer thickness and increase in the replacement rate of the particles when the fluidizing velocity is increased. The increase in the conductive coefficient at the fluidized region of the tube may be the result of the increase in the mobility and effective thermal conductivity of the defluidized particles and a simultaneous decrease in the cap size with increase in velocity. The decrease in the coefficient observed in the stagnation
FIGURE 6.34 VARIATION OF LOCAL CONDUCTIVE HEAT TRANSFER COEFFICIENT WITH FLUIDIZING VELOCITY (EXPERIMENTAL)
FIGURE 6.35 VARIATION OF LOCAL CONDUCTIVE HEAT TRANSFER COEFFICIENT WITH FLUIDIZING VELOCITY (EXPERIMENTAL)
region of the tube may be due to the increase in the
voidage of the emulsion packet with velocity.

At higher temperatures, a larger increase in the
conductive coefficient is observed with increase in velo­
city, more significantly at the fluidized and defluidized
regions. As stated earlier, this increase may be the
result of the increased mobility of the defluidized
particles and their better mixing and replacement rate at
higher velocities and temperatures.

The ratio of the conductive heat transfer coefficient
to their mean values with fluidizing velocity is shown in
Figure 6.36. for a bed temperature of 800°C and a
particle size of 6-0 mm. It is observed that the deviation
of the ratio of the conductive heat transfer coefficient
to their mean values decreases from 45 to 23 percent when
the fluidizing velocity is increased from 0.8 to 1.4 m/s.
This may be due to the increase in the mobility of the
particles at the defluidized region of the tube. Further,
it is seen that the maximum conductive heat transfer
coefficient occurs in the upstream end of the fluidized
region of the tube at the lowest fluidizing velocity of
0.8 m/s, but moves to the downstream side when the
fluidizing velocity is increased. This may be the result
of the decrease in the boundary layer thickness at higher
velocities and increase in the movement of the particles
TUBE OUTER DIAMETER: 60 mm
PARTICLE SIZE: 6.0 mm
BED TEMPERATURE: 800 °C
FLUIDIZING VELOCITY:
- 0.8 m/s
- 1.0 m/s
- 1.2 m/s
- 1.4 m/s

FIGURE 6.36 VARIATION OF LOCAL CONDUCTIVE HEAT TRANSFER COEFFICIENT (DIMENSIONLESS) WITH FLUIDIZING VELOCITY (EXPERIMENTAL)
at the sides of the tube by the rising bubbles with increase in velocity.

The analytical and experimental values of the total and radiative heat transfer coefficients with fluidizing velocity in the defluidized, fluidized and stagnation regions of the tube are shown in Figure 6.37 for a bed temperature of 800°C and a particle size of 6-0 mm. It is observed that the experimental values are in close agreement with the analytical values for the total and radiative heat transfer coefficients, with a deviation of about 7 and 16 percent respectively in the fluidized region. Further, at the stagnation region the experimental values are also in close agreement with the analytical values with a deviation of about 15 and 12 percent respectively for the total and radiative coefficients. At the defluidized region, it is seen that the experimental values are in qualitative agreement with the analytical values. However, the deviation is on the higher side, being about 25 and 40 percent for the total and radiative coefficients. This is mainly due to the restrictive assumptions made in the analysis namely (i) the bed behaves as a packed bed at the top of the tube, and (ii) a constant size of the defluidized cap at all velocities. But in the actual operating condition the defluidized cap size is likely to decrease with velocity. In the absence of detailed information about the bed behaviour in this region, the analysis
FIGURE 6.37 LOCAL HEAT TRANSFER COEFFICIENTS IN THE REGIONS WITH FLUIDIZING VELOCITY

- TUBE OUTER DIAMETER: 60 mm
- PARTICLE SIZE: 6-0 mm
- BED TEMPERATURE: 800°C

- DFR - DEFLUIDIZED REGION
- FR - FLUIDIZED REGION
- SR - STAGNATION REGION
- T - TOTAL HTC
- R - RADIATIVE HTC

LOCAL HEAT TRANSFER COEFFICIENT, WATTS/m²°C

FLUIDIZING VELOCITY, m/s
provides a reasonably good approach in estimating the heat transfer in this region.

The analytical and experimental average values of the heat transfer coefficients with fluidizing velocity are shown in Figure 6.38 for a particle size of 6-0 mm and a bed temperature of 800°C. It is observed that the experimental total and radiative coefficients are in close agreement with the analytical values with a deviation of about 8 and 19 percent respectively. Further, it is observed that the radiative and total coefficients increase with increase in velocity. The increase in the radiative coefficient may be attributed to the increase in the area of the tube contacted by the bubbles. The increase in the total coefficient may be the result of higher replacement rate of the particles around the tube at higher velocities.

6.2.2 Effect of bed temperature

The variation of local total and radiative heat transfer coefficients with bed temperature for a particle size of 6-0 mm and a tube outer diameter of 60 mm at fluidizing velocities of 0.8 and 1.4 m/s are shown in Figure 6.39 to 6.42. An overall increase in the heat transfer coefficients are observed along the periphery of the tube, when the temperature of the bed is increased. The overall increase in the coefficients may be due to the
FIGURE 6.38 AVERAGE HEAT TRANSFER COEFFICIENT WITH FLUIDIZING VELOCITY
Figure 6.39: Variation of Local Total and Radiative Heat Transfer Coefficients with Bed Temperature.

- Tube Outer Diameter: 60mm
- Particle Size: 6-0.028mm
- Fluidizing Velocity: 0-50 m/s
- Bed Temperature:
  - 700°C: T - Total HTC
  - 800°C: - - - - - - - R - Radiative HTC
  - 900°C: - - - - - - -

- Regions:
  - Defluidized Region
  - Fluidized Region
  - Stagnation Region
  - Fluidized Region
  - Defluidized Region

Angle θ from the Top of the Tube.
FIGURE 6.40 VARIATION OF LOCAL TOTAL AND RADIATIVE HEAT TRANSFER COEFFICIENTS WITH BED TEMPERATURE.
FIGURE 6.41 VARIATION OF LOCAL TOTAL AND RADIATIVE HEAT TRANSFER COEFFICIENTS WITH BED TEMPERATURE (EXPERIMENTAL)
FIGURE 6-42 VARIATION OF LOCAL TOTAL AND RADIATIVE HEAT TRANSFER COEFFICIENTS WITH BED TEMPERATURE (EXPERIMENTAL)
intensive movement and higher replacement rate of the burning particles, changes in the thermophysical properties of the bed and the decrease in the boundary layer thickness near the tube surface with increase in temperature. Also, it is seen that the increase in the heat transfer coefficients are more pronounced at the fluidized and defluidized regions of the tube than that at the stagnation region when the bed temperature is increased. This may be because of the fact that, at higher temperatures, the bubble size decreases, but its number increases. This increased number of small bubbles may increase the frequency of replacement and better circulation of the particles at the fluidized and defluidized regions of the tube. Further, it is observed that at higher velocities the increase in coefficients are more significant at the defluidized and fluidized regions of the tube extending from 0 to 100° with increase in bed temperature, compared to that at the upstream side of the tube. The increase in the coefficients in this region may be due to the increase in circulation and vigorous movement of the particles at higher velocities and temperatures.

The circumferential variation of the ratio of total and radiative heat transfer coefficients to their mean values for a fluidizing velocity of 1.0 m/s with bed temperature are shown in Figures 6.43 and 6.44. It is observed that the variation of the local total and radiative heat transfer coefficients decrease from 70 to 18 percent
TUBE OUTER DIAMETER : 60 mm
PARTICLE SIZE : 6~0 mm
FLUIDIZING VELOCITY : 1.0 m/s
BED TEMPERATURE :

700 °C
800 °C
900 °C

FIGURE 6.43 VARIATION OF LOCAL TOTAL HEAT TRANSFER COEFFICIENT (DIMENSIONLESS) WITH BED TEMPERATURE (EXPERIMENTAL)
FIGURE 6.44 VARIATION OF LOCAL RADIATIVE HEAT TRANSFER COEFFICIENT (DIMENSIONLESS) WITH BED TEMPERATURE (EXPERIMENTAL)

TUBE OUTER DIAMETER: 60 mm
PARTICLE SIZE: 6.0 mm
FLUIDIZING VELOCITY: 1.0 m/s
BED TEMPERATURE: 700 °C, 800 °C, 900 °C
and 59 to 26 percent respectively from their mean values when the bed temperature is increased from 700 to 900°C. Further, the maximum heat transfer coefficients occur at the lower portion of the tube for the bed temperature of 700°C and the points of occurrence of maximum coefficients are moved along the sides of the tube when the temperature is increased. This may be because of the increase in number of bubbles, which burst at the sides of the tube, resulting in an increased circulation of the particles with increase in temperature. Further, the exact location of the maximum heat transfer coefficients may depend on the number and size of the bubbles with temperature.

The local variation of the conductive heat transfer coefficient for the above bed parameters with bed temperature for fluidizing velocities of 0.8 and 1.4 m/s are shown in Figures 6.45 and 6.46. It is observed that the conductive heat transfer coefficient increases all along the perimeter of the tube when the temperature is increased. This may be attributed to the decrease in the boundary layer thickness, changes in thermophysical properties of the bed and the intensive movement of the particles with increase in temperature in the fluidized region. At the stagnation region the increase in the coefficients may be due to the changes in the thermophysical properties of the bed. At the defluidized region, the increase in the coefficients may be caused by the higher replacement rate of particles.
TUBE OUTER DIAMETER ; 60 mm
PARTICLE SIZE ; 6-0 mm
FLUIDIZING VELOCITY 0-8 m/s
BED TEMPERATURE ; 700 °C

FIGURE 6.45 VARIATION OF LOCAL CONDUCTIVE HEAT TRANSFER COEFFICIENT WITH BED TEMPERATURE (EXPERIMENTAL)
FIGURE 6.46 VARIATION OF LOCAL CONDUCTIVE HEAT TRANSFER COEFFICIENT WITH BED TEMPERATURE (EXPERIMENTAL)
and the changes in the thermophysical properties of the bed. It is also seen that at higher velocities, the conductive coefficient increases significantly at the fluidized and defluidized regions of the tube, with increase in temperature. This increase may be attributed to the combined effect of temperature and fluidizing velocity in reducing the boundary layer thickness and better mixing of the particles at the fluidized region. In the defluidized region, the increase in the coefficients may be due to the increase in the thermophysical properties of the bed and the increase in the replacement rate of the particles.

The local variation of the ratio of the conductive heat transfer coefficient with temperature at a fluidizing velocity of 1.0 m/s and for a particle size of 6-0 mm is shown in Figure 6.47. It is observed that the variation of conductive coefficient to their mean values reduce from 80 to 43 percent when the temperature is increased from 700 to 900°C. This may be due to the increase in the effective thermal conductivity and higher replacement rate of the particles at the defluidized region of the tube. Further, it is observed that at low temperatures the maximum conductive coefficient occurs at the lower portion of the tube and it moves to the side of the tube with increase in temperature. This phenomenon may be due to the increased circulation of the particles at the sides of the tube by the rising bubbles at high temperatures.
FIGURE 6.47 VARIATION OF LOCAL CONDUCTIVE HEAT TRANSFER COEFFICIENT WITH BED TEMPERATURE (EXPERIMENTAL)
The analytical and experimental values of the total and radiative heat transfer coefficients with bed temperature in the defluidized, fluidized and stagnation regions of the tube are shown in Figure 6.48. It is seen that the experimental values are in close agreement with the analytical values, the deviation being about 9 and 16 percent for the total and radiative coefficients respectively at the fluidized region. Further, at the stagnation region the experimental values are also in close agreement with the analytical values, with a deviation of about 16 and 10 percent for the total and radiative coefficients respectively. At the defluidized region the deviation is higher for the total and radiative coefficients, being about 37 and 50 percent respectively. This is plainly due to the restrictive assumptions made in the analysis.

The average analytical and experimental values of the heat transfer coefficients with bed temperature are shown in Figure 6.49 for a particle size of 6-0 mm and a fluidizing velocity of 1.4 m/s. It is seen that the experimental values of the total and radiative coefficients are in close agreement with the analytical values with a deviation of about 6 and 13 percent respectively. Further, it is observed that the total and radiative coefficients increase with increase in temperature. The increase in the radiative coefficient may be due to the changes in the thermophysical properties of the bed and the increase in
FIGURE 6.48 LOCAL HEAT TRANSFER COEFFICIENTS IN THE REGIONS WITH BED TEMPERATURE
FIGURE 6.49 AVERAGE HEAT TRANSFER COEFFICIENT WITH BED TEMPERATURE

TUBE OUTER DIAMETER: 60 mm
PARTICLE SIZE: 6.0 mm

- ANALYTICAL
- EXPERIMENTAL

TOTAL HTC

RADIATIVE HTC

BED TEMPERATURE, °C

V = 1.4 m/s

O.8

0

20

40

60

80

100

120

140

160
the area of the tube contacted by the bubbles. The increase in the total coefficient may be due to the interplay of bed parameters and the changes in the thermophysical properties of the bed.

6.2.3 Effect of particle size

The variation of local total and radiative heat transfer coefficients with particle size are shown in Figure 6.50 for a fluidizing velocity of 1.0 m/s at a bed temperature of 800°C. It is observed that the variation in particle size has opposite effects on the total and radiative heat transfer coefficients. A decrease in the particle size increases the total coefficient but decreases the radiative coefficient all around the periphery of the tube. The increase in the total heat transfer coefficient with decrease in particle size may be caused by the effect of decrease in residence time and increase in the replacement rate of the particles in the fluidized and stagnation regions of the tube. At the defluidized region the increase in the total coefficient may be due to the mobility of the defluidized particles and the decrease in the gas film thickness near the tube surface. The decrease in the radiative coefficient with decrease in particle size may be because of the faster cooling of the smaller particles near the tube surface in the fluidized region as stated by Zebrodsyky [43]. As the bed is assumed
Figure 6.50 Variation of local total and radiative heat transfer coefficients with particle size.
to be in fluidized condition in the stagnation region also, the same reason can be attributed for the decrease in the radiative coefficient with decrease in particle size. At the defluidized region, the decrease in the radiative coefficient may be due to the reduction in the effective thermal conductivity of the particles with decrease in particle size.

The variation of the ratio of the local total and radiative heat transfer coefficients to their mean values with particle size are shown in Figures 6.51 and 6.52. It is observed that the variation of the total coefficient decreases from 55 to 21 percent from their mean values when the particle size is decreased from 6-0 to 3-0 mm. This may be attributed to the mobility of the defluidized particles at the top of the tube. Further, the variation of the radiative coefficient increases from 33 to 57 percent from their mean values when the particle size is decreased from 6-0 to 3-0 mm. This may be due to the lower temperature of the smaller particles at the defluidized region.

The local variation of the conductive heat transfer coefficients for the above bed parameters is shown in Figure 6.53. An overall increase in the conductive coefficient is observed around the tube surface, when the particle size is decreased. Further, the increase is more significant in the defluidized region. The overall increase
TUBE OUTER DIAMETER: 60 mm
FLUIDIZING VELOCITY : 1.0 m/s
BED TEMPERATURE : 800 °C
PARTICLE SIZE:
- - - - - - - - - - - - - - - - - - - - - - - - - 6.0 mm
- - - - - - - - - - - - - - - - - - - - - - - - - 5.0 mm
- - - - - - - - - - - - - - - - - - - - - - - - - 4.0 mm
- - - - - - - - - - - - - - - - - - - - - - - - - 3.0 mm

FIGURE 6.51 VARIATION OF TOTAL HEAT TRANSFER COEFFICIENT (DIMENSIONLESS) WITH PARTICLE SIZE
FIGURE 6.52 Variation of radiative heat transfer coefficient (dimensionless) with particle size.
FIGURE 6.53 VARIATION OF LOCAL CONDUCTIVE HEAT TRANSFER COEFFICIENT WITH PARTICLE SIZE (EXPERIMENTAL)

TUBE OUTER DIAMETER: 60 mm
FLUIDIZING VELOCITY: 1.0 m/s
BED TEMPERATURE: 800 °C

PARTICLE SIZE:
- 6-0 mm
- 5-0 mm
- 4-0 mm
- 3-0 mm
in the coefficient may be due to the higher replacement rate of the smaller particles in all the regions of the tube. The significant increase in the coefficient in the defluidized region may be due to the bursting of bubbles which increases the circulation of smaller particles in this region. Further, at the defluidized region the gas film resistance decreases with decrease in particle size. Figure 6.54 shows the variation of the ratio of the local conductive coefficient with their mean values for the above bed parameters. It is observed that the variation of the conductive coefficient decreases from 60 to 21 percent when the particle size is decreased from 6-0 to 3-0 mm. This may be due to the mobility of the smaller particles at the defluidized region of the tube.

The analytical and experimental values of the total and radiative heat transfer coefficients with particle size in the fluidized, defluidized and stagnation regions of the tube are shown in Figure 6.55, for a bed temperature of 800°C and a fluidizing velocity of 1.0 m/s. It is observed that at the fluidized region the experimental values of the total coefficient is in close agreement with the analytical values with a deviation of about 10 percent, but the deviation of the radiative coefficient is on higher side being about 38 percent. This may be due to the higher rate of cooling of the smaller particles, caused by their lower thermal capacity. At the stagnation region the
TUBE OUTER DIAMETER : 60 mm
FLUIDIZING VELOCITY : 1.0 m/s
BED TEMPERATURE : 800 °C
PARTICLE SIZE :
- 6-0 mm
- 5-0 mm
- 4-0 mm
- 3-0 mm

FIGURE 6.54 VARIATION OF CONDUCTIVE HEAT TRANSFER COEFFICIENT (DIMENSIONLESS) WITH PARTICLE SIZE
BED TEMPERATURE: 800°C
PARTICLE SIZE: 6-0 mm
FLUIDIZING VELOCITY: 1.0 m/s

**DFR** - DEFLUIDIZED REGION
**FR** - FLUIDIZED REGION
**SR** - STAGNATION REGION

**T** - TOTAL HTC
**R** - RADIATIVE HTC

**ANALYTICAL**
**EXPERIMENTAL**

**FIGURE 6.55 LOCAL HEAT TRANSFER COEFFICIENTS IN THE REGIONS WITH PARTICLE SIZE**
experimental values are in close agreement with the analytical values, being about 12 percent for the total coefficient and 20 percent for the radiative coefficient. Moreover, it is seen that the experimental values are in qualitative agreement with the analytical values in the defluidized region. However, the deviation of the heat transfer coefficients are on the higher side, being about 30 percent for the total coefficient and 55 percent for the radiative coefficient. This is merely due to the restrictive assumptions of the analysis as stated earlier.

The average analytical and experimental values of the heat transfer coefficients with particle size are shown in Figure 6.56 for a bed temperature of 800°C and a fluidizing velocity of 1.0 m/s. It is observed that the experimental total and radiative coefficients are in close agreement with the analytical values, with a deviation of about 6 and 15 percent respectively.

6.2.4 Effect of tube size

The variation of the local total and radiative heat transfer coefficients with tube size is shown in Figure 6.57 for a bed temperature of 800°C and particle size 6-0 mm at a fluidizing velocity of 1.0 m/s. An overall increase in heat transfer coefficients are observed along the circumference of the tube when the tube diameter is decreased. Further, it is seen that the increase in the
FIGURE 6.56 AVERAGE HEAT TRANSFER COEFFICIENTS WITH PARTICLE SIZE
Figure 6.57 Variation of local total and radiative heat transfer coefficients with tube size.

Bed temperature: 800 °C
Fluidizing velocity: 1.0 m/s
Particle size: 6.0 mm
Tube outer diameter:
- 60 mm
- 50 mm
- 42 mm
- 32 mm

Key:
- T—Total HTC
- R—Radiative HTC

Regions:
- Deaerated region
- Fluidized region
- Stagnation region
- Deaerated region

Angle Φ from the top of the tube.
total coefficient is significant at the defluidized and upper portion of the fluidized region of the tube extending from 0 to 90°. The overall increase in the coefficient may be due to the decrease in the residence time of the particles around the smaller diameter tubes as stated by Shah et al. [44]. This may be explained further by the fact that the decrease in the residence time increases the temperature of the emulsion packet and hence the total and radiative heat transfer coefficients. Further, the boundary layer thickness decreases with decrease in tube diameter, resulting in an increase in the total heat transfer coefficient at the fluidized and stagnation regions of the tube. At the defluidized region, the cap size and the turnover time decreases with decrease in tube diameter [33] and this may be the cause of increased heat transfer coefficients. The higher heat transfer in the defluidized and in the upper portion of the fluidized region may be because of the decrease in the turnover time at the defluidized region and increase in the circulation of the particles in the upper region of the tube by the bursting of rising bubbles.

The variation of the ratio of the local total and radiative heat transfer coefficients to their mean values with tube size are shown in Figures 6.58 and 6.59. It is found that the variation of the total heat transfer coefficient decreases from 55 to 27 percent and radiative
PARTICLE SIZE : 6.0 mm
FLUIDIZING VELOCITY : 1.0 m/s
BED TEMPERATURE : 800°C
TUBE OUTER DIAMETER:
- - - - - - - - - - 60 mm
- - - - - - - - - - 50 mm
- - - - - - - - - - 42 mm
- - - - - - - - - - 32 mm

FIGURE 6.58 VARIATION OF TOTAL HEAT TRANSFER COEFFICIENT (DIMENSIONLESS) WITH TUBE SIZE (EXPERIMENTAL)
PARTICLE SIZE : 6.0 mm
FLUIDIZING VELOCITY : 1.0 m/s
BED TEMPERATURE : 800 °C
TUBE OUTER DIAMETER:

60 mm
50 mm
42 mm
32 mm

FIGURE 6.59 VARIATION OF RADIATIVE HEAT TRANSFER COEFFICIENT (DIMENSIONLESS) WITH TUBE SIZE (EXPERIMENTAL)
coefficient from 42 to 24 percent from their mean values when the tube outer diameter is decreased from 60 to 32 mm resulting in a more uniform heat transfer along the circumference of the smaller diameter tubes. This phenomenon may be attributed to the decrease in the defluidized cap size and turnover time with decrease in tube diameter.

The variation of the local conductive heat transfer coefficient with tube size for a bed temperature of 800°C, particle size of 6-0 mm at a fluidizing velocity of 1.0 m/s is shown in Figure 6.60. It is seen that the conductive coefficient increases all over the tube surface as the tube diameter is decreased. The overall increase in the coefficient may be due to the decrease in the boundary layer thickness at the fluidized region and the decrease in the cap size in the defluidized region of the tube with decrease in tube diameter. At the stagnation region, this may be because of the decrease in the gas film thickness for the decrease in tube diameter, as it grows around the tube surface with increase in tube diameter, as stated by Shah et al [44]. The higher increase at the defluidized region of the tube may be due to the decrease in the turnover time of the smaller defluidized cap. Further, the lower edge of the defluidized cap is constantly washed by the gas stream as stated by Syromyatnikov [31] and this combined with higher renewal rate of the defluidized cap.
PARTICLE size : 6-0 mm
FLUIDIZING VELOCITY : 1-0 m/s
BED TEMPERATURE : 800 °C
TUBE OUTER DIAMETER :

- - - - - - - - - - - - - 60 mm
- - - - - - - - - - - - - 50 mm
- - - - - - - - - - - - - 42 mm
- - - - - - - - - - - - - 32 mm

FIGURE 6.60 VARIATION OF LOCAL CONDUCTIVE HEAT TRANSFER COEFFICIENT WITH TUBE SIZE (EXPERIMENTAL)
increase the circulation of the particles at the defluidized region and the upper portion of the fluidized region.

The ratio of the local variation of conductive heat transfer coefficient to their mean values with tube size for the above bed parameters is shown in Figure 6.61. It is found that the variation of the local conductive coefficient decreases from 58 to 32 percent from their mean values when the tube diameter is decreased from 60 to 32 mm. This may be due to the decrease in the turnover time and smaller size of the defluidized cap at the top of the tube.

The analytical and experimental values of the total and radiative heat transfer coefficients with tube size in the fluidized, defluidized and stagnation regions of the tube are shown in Figure 6.62 for a bed temperature of 800°C and a particle size of 6-0 mm. It is observed that the experimental values of total and radiative coefficients are in close agreement with analytical values, with a deviation of about 10 and 12 percent respectively. Further, at the stagnation region, the experimental values are also in close agreement with the analytical values for the total and radiative coefficients, with a deviation of about 11 and 10 percent respectively. At the defluidized region, it is also noticed that the experimental values are in qualitative agreement with the analytical values. However,
FIGURE 6.61 VARIATION OF LOCAL CONDUCTIVE HEAT TRANSFER COEFFICIENT (DIMENSIONLESS) WITH TUBE SIZE (EXPERIMENTAL)
FIGURE 6.62 LOCAL HEAT TRANSFER COEFFICIENTS IN THE REGIONS WITH TUBE SIZE

- DFR - DEFUIDIZED REGION
- FR - FLUIDIZED REGION
- SR - STAGNATION REGION
- T - TOTAL HTC
- R - RADIATIVE HTC
the deviation is on the higher side, being about 29 percent for the total coefficient and 53 percent for the radiative coefficient. This is plainly due to the restrictive assumptions made in the analyses.

The average analytical and experimental values of the heat transfer coefficients with tube size are shown in Figure 6.63 for a particle size of 6-0 mm and a bed temperature of 800°C. It is observed that the experimental total and radiative coefficients are in close agreement with the analytical values with a deviation of about 12 and 21 percent respectively. Further, it is found that the heat transfer coefficients are decreasing with increase in tube diameter. This may be due to the increase in the residence time of the particles around the bigger diameter tubes and the increase in the boundary layer thickness with increase in tube size.
FIGURE 6.63 AVERAGE HEAT TRANSFER COEFFICIENT WITH TUBE SIZE