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Parametric Performance Studies On Fluidized-
Bed Heat Exchangers ✓

Yearly Technical Progress Report
Task I - Fouling Characteristics
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ABSTRACT

Analyses and experiments are being performed in this program to investigate the heat transfer performance of single and multi-stage shallow fluidized beds for application to the recovery of heat from sources such as waste heat, and coal combustion or coal gasification. The work, which is an extension of that done previously under contracts EC-77-C-03-1433 and DE-AC03-79-ET11348, consists of three tasks. In Task 1, tests have been conducted to investigate the effects of liquid condensate fouling on fluidized bed heat exchanger performance. Liquid condensates used in these tests were water and glycerol (which is more viscous than water). The tests showed that fluidized bed heat exchanger performance is degraded by condensation within the bed and the degradation is caused by bed particles adhering to the heat exchanger surface, not by particle agglomeration. Liquid condensate did not continuously build up within the bed. After a period of dry-out, heat transfer equal to that obtained prior to condensation was again obtained.

This work discussed in this report was sponsored by the U.S. Department of Energy and represents Task 1 of DOE Contract DE-AC22-81-PC40280. The contract was monitored through the Pittsburgh Energy Technology Center.

CONCLUSIONS

The following conclusions result from tests with liquid condensate fouling in fluidized bed heat exchangers:

1. Heat exchanger performance is degraded when the dew point temperature exceeds the heat exchanger surface temperature.

2. The performance decrease occurs as a result of particle adherence to the heat exchanger surface and not as a result of particle agglomeration, however, when the dew point becomes greater than the bed temperature the bed particles do agglomerate resulting in cessation of all fluidization.

3. The degree of fluidization (or value of superficial velocity, V_s) does not appear to change the manner in which condensation affects the heat exchanger performance over a range of V_s from 0.4 to 0.6 in/sec.

4. Changing the bed material from spherical glass beads to irregularly shaped Al_2O_3 particles did not alter the manner in which condensation affects the heat exchanger performance.

5. The dew points upstream and downstream of the bed are the same; thus, the heat transfer coefficient between the bed and the heat exchanger surface adjusts so there is no condensate build-up.

6. Original heat exchanger performance can be attained after condensation has occurred by operating the bed in the dry state for several hours. This allows the residual condensate to evaporate, and the scrubbing action of the bed to abrade away bed particles which had adhered to the heat exchanger surfaces.

INTRODUCTION

Shallow fluidized bed heat exchangers (FBHEX) for use in waste heat recovery systems have been investigated at United Technologies Research Center since 1977 (DOE contracts EC77-C-03-1433 and DEAC03-79-ET 11348). These studies (Ref. 1 and 2) consisted of: a) tests to measure FBHEX performance, and b) comparisons of FBHEX with conventional heat exchangers for specific heat transfer tasks. The conclusions obtained in Refs. 1 and 2 were that in a FBHEX the heat transfer coefficient may be enhanced as much as a factor of 5 but the inherent lower velocities of a FBHEX result in the size and cost of the FBHEX being nearly the same as a conventional heat exchanger. However, there are certain situations where a FBHEX has some definite advantages. Heat transfer at a high rate with small heat exchanger pressure loss is an application where a FBHEX can outperform a conventional heat exchanger. FBHEX pressure losses are typically a few inches of water. Means for further reducing these losses were studied in Ref. 2.

Heat transfer in fouling environments is another situation where a FBHEX may be very useful. Fouling by either solid or liquid condensates can greatly reduce the effectiveness of heat exchanger surfaces. Solid condensates can result from solid particles present in the exhaust gas from a coal combustor or a diesel engine or can occur as a result of vapor freezing on the heat exchanger surface as with frost on freezer heat exchanger coils. Liquid condensate can occur on heat exchanger surfaces in the exhaust from coal gasifiers, coal dryers, or waste heat recovery devices. A fluidized bed may be expected to be resistant to solid condensate fouling because of the scrubbing action of the particles on the heat exchanger surface. This was demonstrated to some extent in Ref. 1, and to a greater extent in Ref. 3; in the latter case fouling of the distributor plate did occur, but was easily removed. The self cleaning action of a FBHEX in the presence of solid condensates is an advantage which a conventional heat exchanger does not have.

Liquid condensation in heat exchangers also reduces their effectiveness. In a FBHEX the condensation may occur on heat exchanger surfaces or within the bed material itself. If it occurs on the surface, the bed particles may transport the liquid from the surface into the hotter bed region where it re-evaporates. If this occurs, the onset of any performance degradation may be delayed. If the liquid condensate forms in the bed, the particles will agglomerate and fluidization of the bed will be reduced or cease. However, if condensation is at a low rate, it may be possible to continuously remove wet particles and replace them with dry particles, thus maintaining a deagglomerated bed.

The objective of the work reported here are to conduct experiments to investigate the performance of a FBHEX operating in a liquid condensate fouling environment. This work comprises the first half of DOE Contract DE-AC22-81-PC40280 and is denoted as Task 1, the effects of condensate fouling on heat exchanger performance. Task 2, the performance of staged heat exchangers separated by horizontal baffles and Task 3, the effects of heat exchanger surface geometry on performance will be conducted subsequently. The work accomplished under Task 1 is discussed in the following sections.

EXPERIMENTAL EQUIPMENT AND PROCEDURE

The shallow fluidized bed heat exchanger (FBHEX) used in the previous program and described in Ref. 2 was modified so that water or glycerol could be injected as a spray of fine drops into the plenum and evaporated into the inlet airstream upstream of the distributor plate and fluidized bed. A sketch of the unit used for tests with liquid condensate fouling is shown in Fig. 1 and a schematic showing air, cooling water, and liquid injection flow circuits is given in Fig. 2.

Air System

A blower rated at 736 l/m (2600 CFM) at 63.5 cm (25 in) H_2O pressure rise is used to supply air to fluidize the bed. The blower discharge air passes over electric heaters mounted within a duct adjacent to the heat exchanger (see Fig. 2). The heater is a 60 kW, 480 V unit connected into four manually controlled circuits of 6, 12, 18 and 24 kW capacity. Air temperature up to approximately $204^\circ C$ ($400^\circ F$) can be obtained. After passing through the heater, the air passes through a butterfly control valve into the plenum beneath the fluidized bed. The air then passes through the distributor plate and fluidized bed into the freeboard region and then exhausts to atmosphere. Air flow rates (and hence superficial velocity) were controlled using the butterfly valve and were measured using a 7.6 cm (3 in.)-dia ASME nozzle installed according to ASME standards in the ducting downstream of the bed. The nozzle differential pressure was measured using an inclined manometer having a resolution of 0.0254 cm (0.01 in.) H_2O .

The air temperatures were measured at the heater inlet and exit, in the air inlet plenum, in the bed, and at the fluidized bed heat exchanger exhaust. The locations for temperature measurement are shown in Fig. 2. The temperature in the inlet plenum was measured using a shielded aspirated thermocouple, whereas the other temperatures were measured using bare thermocouple beads. The thermocouple outputs were measured with a digital voltmeter. An ice point reference junction was used in all tests.

Water Flow Systems

The heat loss from the air was transferred to water passing through the finned tubes located within the fluidized bed. Water was supplied to the heat exchanger using two methods. In fouling tests with water injection, the cooling water was supplied from city water at approximately $10^\circ C$ ($50^\circ F$) and exhausted to drain. In fouling tests with glycerol injection, the cooling water was circulated through the tubes using a pump with cool water added to and hot water drained from the flow to maintain a constant inlet water temperature of approximately $60^\circ C$ ($140^\circ F$). This circuit is shown in Fig. 2. A temperature control valve in the drain line was used to control the rate of hot water drained from the circuit. The water flow rate was measured with rotameters calibrated by measuring the weight of the water flowing through the rotameters in a known period of time. The temperature of the water was measured using thermocouples and the water flow rate measurements were corrected for water density variations. The temperature rise of the water and water flow rate were

used to calculate the heat transferred to the water.

Foulant Injection System

Fouling condensates were injected as liquids through an Unijet nozzle with a flat spray tip to spray fine liquid droplets into the high temperature inlet airstream where the drops evaporated. The injection system is shown in Fig. 2. Either water or glycerol were injected. The water was supplied at city water pressure and the rate of injection measured using a calibrated flowmeter. The glycerol was supplied from a heating vessel pressurized with air and its rate of injection also measured using a calibrated flowmeter. The glycerol was heated to reduce its viscosity and permit easier injection into the air system.

The water dew points in the inlet plenum and freeboard region were measured using a General Eastern Inc. 1200 APS dew point hygrometer (see Fig. 2). The water dew point in the inlet plenum was also determined from measured water injection and air flow rates. As will be discussed in a following section, the two methods of determining the water dew point were in good agreement and it was concluded that the dew point in the inlet plenum could be accurately determined from measured flow rates. This method was then employed for determining the dew point in the inlet plenum with glycerol injected as the condensate.

Bed Material Exchange System

In one test with water injected into the inlet air stream bed material was removed in a controlled manner by entrainment into air evacuated through a vacuum pump and fresh bed material was added by gravity feed at a rate equal to the removal rate. This bed material exchange system is shown schematically in Fig. 2. The rate of removal of bed material was controlled by adjustment of the pressure in the hopper used to collect the used bed material and thus the entraining air flow rate. The rate of addition of fresh bed material by gravity feed from the fresh bed material hopper was controlled by varying the size of an orifice located at the exit of the fresh bed material supply duct.

Calculation of Heat Transfer Coefficient

Two analytical models were developed in Ref. 4 for characterizing the fluidized bed. In one model, the bed is assumed to be completely mixed horizontally, in the other the bed is assumed to be distributed with no horizontal mixing. Measurements made of the horizontal temperature distribution (Ref. 1) in a fluidized bed indicated that mixing in a real fluidized bed is between that of the two models. However, for the test condition of this program ($NTU < 6$ and $C_{min}/C_{max} > 0.2$) heat transfer coefficients predicted using either of the two models differ by less than 1.25 percent. For simplicity, the mixed bed model was assumed in the calculation of the heat exchanger's overall heat transfer coefficient from the measured temperatures and flow rates. The equations used in this calculation are given in Appendix I of Ref. 2.

The overall heat transfer coefficient, U , results from forced

convection between the water and the tube wall (film coefficient, h_w), conduction through the tube wall and fins (thermal conductivity, k), and heat transfer from the fluidized bed to the finned tubes (bed heat transfer coefficient, H_b). The former two were calculated using equations described in Appendix I of Ref. 2 (also see Appendix I of Ref. 1), and were used with the equations for the overall heat transfer coefficient to calculate the bed heat transfer coefficient, H_b .

Determination of the overall heat transfer coefficient, U , was made from the heat transferred to the water and the fluidized bed temperature. The latter was determined by averaging bed temperatures measured at four equally spaced locations along the heat exchanger.

DISCUSSION OF TESTS

Tests were conducted using the shallow fluidized bed heat exchanger facility to investigate the effect of liquid condensate fouling on heat exchanger performance. The twelve-tube Fluidfire heat exchanger and the Fluidfire distributor plate having approximately 2.4 percent open area were used in these tests (see Ref. 1 for descriptions of the heat exchanger and distributor plate geometry). The bed material was either spherical glass beads or irregularly shaped Al_2O_3 having nominal sizes of 280 and 363 micrometers, respectively. The depth of the bed material (bed in quiescent state) was just enough to cover the top of the fins. Tests were conducted using either water or glycerol as the foulants. Table I lists some operating temperatures encountered in the injection tests, and Table II presents properties of the water and glycerol injectant. As previously stated, the glycerol was selected because of its large viscosity.

Water Foulant Tests

Tests were conducted with water injected into the heated inlet air flow upstream of the distributor plate. Vaporization of the water droplets occurred in the inlet plenum such that air and water vapor passed through the distributor plate. The temperature of the heat exchanger was adjusted to be below the dew point thus causing condensation. The injection rate of water was varied to provide dew point temperatures ranging from 30°C (54°F) less than the heat exchanger surface temperature to 20°C (36°F) greater than the surface temperature. In all tests the dew point temperature was less than the bed temperature. Dew points measured using the General Eastern Inc. 1200 APS system dew point hygrometer in air samples taken from the inlet plenum upstream of the distributor plate and the freeboard region downstream of the fluidized bed are compared, in Fig. 3, with dew point temperatures calculated using measured values of air and injectant flow rate. Measured upstream and downstream dew points are denoted by the circular and square symbols, respectively. Good agreement exists between measured dew points (using the hygrometer) and those calculated using flow rates. This agreement substantiates the complete vaporization of the water droplets prior to flowing through the distributor plate.

Figure 3 also shows the upstream and downstream dew points are approximately equal even for dew point temperatures greater than about 20°C for which condensation occurs on the heat exchanger surface. This indicates that when condensation does occur there is no build up of the condensate. Instead, particles adhere to the surface causing reduced heat transfer and higher "surface" temperatures so that moisture is re-evaporated at the same rate that it condenses and an equilibrium condition is obtained. Thus the dew point of the upstream and downstream air is the same.

Performance with Water Foulant and Bed of 280 Micrometer Glass Beads

Data obtained in tests with water injected into the inlet air stream upstream of the distributor plate are presented in Fig. 4 for a bed of 280 micrometer glass beads and for superficial velocities, V_s , of 0.4,

0.48, 0.6 m/s. The data are presented as variations of heat transfer film coefficients, H_b , and nondimensionalized Nusselt numbers, $Nu = H_b D / K_a$ (where D is the bed particle nominal size and K_a is the thermal conductivity of air), with the difference between the dew point temperature and the heat exchanger surface temperature.

The data indicates that performance is not affected by the injected water (or increasing dew point) until enough water is added to make the dew point equal to the heat exchanger surface temperature. For dew point temperature greater than the heat exchanger surface temperature, performance is seriously degraded. For dew point temperatures 20°C greater than the heat exchanger wall temperature, the performance was about 1/3 of its value without water injection. The data also indicate that the performance and the effect of dew point temperature on performance degradation is not appreciably affected by the amount of fluidization (i.e., value of V_s).

Observation of the bed during tests with condensation indicated that the performance degradation resulted from particles adhering to the heat exchanger surfaces and not from particle agglomeration. Photographs showing the FBHEX surfaces before and after condensation are shown in Fig. 5. In Fig. 5a, the fins are shown to be free of bed particles prior to condensation and, in Fig. 5b, the fins are shown with bed particles adhering to the surfaces. It was noted that particles in the bed region between fin tubes remained fluidized while fluidization decreased in the bed region over the fin tubes, probably as a result of blockage of air passing between the fins by particles adhering to the fins and tube surface. In Fig. 5c, the fin tubes are shown with the loose bed material removed to make the bed material adhering to the fin tube's surfaces more evident.

Prior to those experiments it was not known how moisture condensation would cause the heat exchanger performance to be altered. However, it appeared that if wet bed material could be removed and dry bed material added (at equal rates), the amount of performance degradation might be minimized. Therefore apparatus was installed in the FBHEX for the controlled removal of bed material (by entrainment into air evacuated through a vacuum pump), and the controlled addition of an equal amount of bed material by gravity feed (Fig. 2). Had the condensation resulted in agglomerations of particles which could have been removed by air entrainment, this method for enhancing performance would have been viable. However, as was discovered, condensation resulted in particles adhering to heat exchanger surfaces. To confirm that performance would be unaffected by bed material changes during testing, a test was conducted with bed material being continuously removed and simultaneously replaced with fresh material at such rates that approximately 10 percent of the bed material was exchanged per hour. The data obtained in this test are presented in Fig. 4 (flagged triangles) and indicate that the exchange of bed material did not affect the heat transfer performance significantly.

Subsequent to the tests with water condensate, data were obtained without water injection to determine if, after dryout, the performance would be restored to the original levels obtained before water injection. Data was obtained 1/2 and 2 hours after dryout and are compared with data

obtained before water injection in Fig. 6. The data indicate that after 1/2 hour of dryout the performance was approximately 3 percent less than the original performance. Examination of the FBHEX revealed that, although most of the bed material which was "caked" between fins and on the tube surfaces had been abraded away, a small amount remained caked between fins on the tops of the heat exchanger tubes. Such caked material could insulate these areas of tube surface from fluidizing action of the bed and account for the decreased heat transfer. The data obtained 2 hours after dryout are in good agreement with original data indicating that the fluidizing action of the bed has abraded away the caked material from the heat exchanger surfaces resulting in the attainment of original heat exchanger performance.

Performance with Water Foulant and 363 Micrometer Aluminum Particles

FBHEX performance tests with vapor injection were made using irregularly shaped Al_2O_3 bed particles of nominal 363 micrometer size to determine if particle shape or material affected the way heat exchanger performance was degraded by condensation in the bed. Data obtained in these tests are compared with data obtained using spherical glass beads in Fig. 7. The data indicate that the change in bed particle shape and material did not significantly change the way performance was affected by moisture condensation. As in previous tests with glass beads, the heat exchanger performance (i.e. the bed side heat transfer coefficient) is degraded when the dew point temperature exceeds the heat exchanger wall temperature and, as has been previously observed, the decrease in heat transfer coefficient occurs as a result of particle adherence to the heat exchanger surface and not as a result of particle agglomeration.

Glycerol Foulant Tests

Tests were conducted with glycerol injected into the inlet airflow upstream of the distributor plate to investigate the effects of a high viscosity condensate on the performance of the FBHEX. In these tests, glass beads having a nominal size of 280 micrometers were used as the bed material (the bed in its quiescent state was just deep enough to cover the fins). The injection rate of glycerol was varied to provide dew point temperature ranging from 95°C (171°F) less than the heat exchanger surface temperature to 13°C (24°F) greater than the surface temperature, and in one test glycerol was injected at a high rate such that the dew point temperature was approximately 72C (130F) greater than the temperature of the bed. For all tests except this one test, the dew point was less than the bed temperature. Tests were conducted for V_g of 0.5 and 0.6 m/s. Prior to tests with glycerol injection, tests⁵ were again conducted to establish baseline performance for comparison with performance during and after glycerol injection.

In the tests with glycerol injection, the General Eastern 1200 APS system dew point hygrometer could not be used with any reliability. (Cracking of the glycerol on the heated mirror surface of the hygrometer caused the instrument to malfunction.) However, as was shown in the tests with water injection, the upstream dew point could be accurately determined

from the measured flow rates of air and the injectant and there was no change in dew point in passing through the bed. Hence, this method was employed for glycerol dew point determination. (Other methods of determining the dew point of glycerol, such as mass spectrometry were investigated but found to be difficult and time consuming to implement in addition to being none too accurate.)

Figure 8 presents the FBHEX data obtained with glycerol injection where the variation of heat transfer coefficient and Nusselt number with the temperature difference between the heat exchanger surface and the upstream dew point is shown. As with the water vapor tests, the data in Fig. 8 shows that when the dew point of glycerol becomes greater than the heat exchanger wall temperature the performance is seriously degraded. The degradation in performance was similar to that which occurred when water was injected into the inlet air stream and resulted from adherence of the particles to the heat exchanger fins and tube surfaces. The particles in the bed did not agglomerate until the glycerol dew point temperature was greater than the bed temperature. In one test in which the glycerol dew point was significantly greater than the temperature of the bed material, the bed did agglomerate resulting in the cessation of all fluidization.

Performance data were obtained subsequent to glycerol injection and after the FBHEX had been operated for a sufficient time, without glycerol injection, for the bed to "dry out". The data is compared with data obtained before glycerol injection in Fig. 9. The comparison indicates that after the bed had dried out, original performance was attained. The time required for dryout was 5 to 6 hours after glycerol injection compared to 1 to 2 hours following water injection. This is not surprising since the vapor pressure of water is much higher than that of glycerol at the temperature of the heat exchanger surfaces in these experiments.

In comparing data obtained with water and glycerol injection, (viz Figs. 4 and 8) there appears to be little effect due to the viscosity of the condensate. The primary effect was length of time to dry-out, and this appears to be a function of the vapor pressure of the condensate at the heat exchanger surface temperature.

Although FBHEX performance was degraded by liquid condensation occurring within the bed, no accumulation of condensate occurred, and original heat transfer performance was restored after a sufficient dry-out period. Direct comparison under similar fouling conditions with a conventional heat exchanger cannot be made at the present time. It is, however, expected that the performance of a conventional heat exchanger would also be degraded by liquid condensate and would also recover after a dryout period. Whether the particles adhering to the surface in a FBHEX results in a more severe performance degradation than liquid condensate on a conventional heat exchanger would be an interesting study.

REFERENCES

1. Cole, W. E.: Investigation of Waste Heat Recovery Utilizing Fluidized Bed Heat Exchangers. United Technologies Research Center Report R78-912942, November, 1978.
2. Stoeffler, R. C.: Enhancement of Heat Transfer in Waste-Heat Exchangers. United Technologies Research Center Report R80-914653-15, July 1980.
3. Cusdin, D. R. and M. J. Virr: A Marine Fluidized Bed Waste Heat Boiler, Design and Operation Experience, Trans. I., Mar. E., Vol. 91, 1979.
4. Suo, M.: Calculations Methods for Performance of Heat Exchangers Enhanced with Fluidized Beds. Letters in Heat & Mass Transfer, Vol. 3, 1976, p. 555.

List of Symbols

A	Heat Exchanger surface area, M^2
C_{min}	Minimum heat flow capacity, W/C
C_{max}	Maximum heat flow capacity, W/C
D_p	Particle diameter, micrometers or meters
H_B	Bed side heat transfer coefficient, W/m^2-C
h_W	Water side heat transfer coefficient, W/m^2-C
K_a	Air thermal conductivity, W/m-C
k	heat exchanger thermal conductivity, W/m-C
NTU	Thermal transfer unit NTU - AU/C_{min}
N_u	Nusselt number, $N_u = H_B D_p / K_a$
T_s	Heat Exchanger surface temperature, C
T_B	Bed temperature, C
T_{DP}	Dew point temperature, C
U	Overall heat transfer coefficient, W/m^2-C
V_s	Superficial velocity, m/s

TABLE I: OPERATING TEMPERATURES

INJECTANT	WATER	GLYCEROL
Surface Temp. Range, T_s - C (F)	16-25 (61-77)	70-76 (158-169)
Bed Temp. Range, T_B - C (F)	41-58 (106-136)	80-100 (176-212)
Dew point temp. range, T_{DP} - C (F)	0-35 (32-95)	66-85 (150-185)*

*For one test dew point temp. was 121 C (250 F)

TABLE II: PROPERTIES OF INJECTANTS

INJECTANT	WATER	GLYCEROL
Viscosity at T_s centipoises (lb-sec/ft ²)	0.95 (1.94×10^{-5})	59-42 (1.2×10^{-3} - 8.5×10^{-4})
Specific Heat, Kcal/kgm-C	1.00	.58
Density, gm/cm ³ (lb/ft ³)	1.0 (62.4)	1.228 (76.5)
Surface Tension, dyne/cm	71.9	63.5

DETAILS OF UTRC FLUIDIZED BED HEAT EXCHANGER
MANUFACTURED BY STONE-PLATT FLUIDFIRE LTD

FIG. 1

SCHEMATIC OF FLUIDIZED BED HEAT EXCHANGER

FIG. 2

COMPARISON OF CALCULATED AND MEASURED DEW POINTS

WATER INJECTANT

SYMBOL	LOCATION
○	UPSTREAM OF DISTRIBUTOR PLATE
□	DOWNSTREAM OF FLUIDIZED BED

**VARIATION OF HEAT TRANSFER PARAMETERS WITH TEMPERATURE
DIFFERENCE BETWEEN DEW POINT OF WATER AND HEX WALL FOR SEVERAL
SUPERFICIAL VELOCITIES**

SYMBOL	SUPERFICIAL VELOCITY, V_s — M/S
○	0.48
□	0.60
△	0.40

- NOTE: 1) OPEN AND CLOSED SYMBOLS DENOTE H_B AND Nu RESPECTIVELY
 2) GLASS BEAD BED MATERIAL NOMINAL SIZE = $280\mu m$
 3) FLAG DENOTES SIMULTANEOUS ADDITION AND REMOVAL OF BED MATERIAL

PHOTOGRAPHS OF FBHEX SURFACES BEFORE AND AFTER WATER CONDENSATION

QUIESCENT BED

a) BEFORE CONDENSATION

b) AFTER CONDENSATION

c) AFTER CONDENSATION WITH LOOSE
BED MATERIAL REMOVED

VARIATION OF HEAT TRANSFER PARAMETERS WITH SUPERFICIAL VELOCITY BEFORE AND AFTER WATER INJECTION

SYMBOL	COMMENT
○	BEFORE WATER INJECTION
△	1/2 HOUR AFTER WATER INJECTION AND DRY OUT
□	2 HOURS AFTER DRY OUT

NOMINAL BED PARTICLE DIAMETER = 280 μm

VARIATION OF HEAT TRANSFER PARAMETERS WITH TEMPERATURE DIFFERENCE BETWEEN WATER DEW POINT AND HEX WALL FOR TWO DIFFERENT BED MATERIALS

SYMBOL	BED MATERIAL	NOMINAL SIZE — μm	SHAPE	SUPERFICIAL VELOCITY, V_s — m/s
— $\square$ —	GLASS BEADS	280	SPHERICAL	0.60
— $\diamond$ —	Al_2O_3	363	IRREGULAR	0.66

NOTE: OPEN AND CLOSED SYMBOLS DENOTE H_B AND Nu RESPECTIVELY

**VARIATION OF HEAT TRANSFER PARAMETERS WITH TEMPERATURE DIFFERENCE
BETWEEN DEW POINT OF GLYCEROL AND HEX WALL TEMPERATURE
FOR TWO SUPERFICIAL VELOCITIES**

SYMBOL	V_S -m/s
○	0.5
□	0.6

NOTE: GLASS BEAD BED MATERIAL
NOMINAL DIAMETER = 280 μm

VARIATION OF HEAT TRANSFER PARAMETERS WITH SUPERFICIAL VELOCITY BEFORE AND AFTER GLYCEROL INJECTION

SYMBOL	COMMENT
○	BEFORE GLYCEROL INJECTION
□	AFTER "DRYOUT" SUBSEQUENT TO GLYCEROL INJECTION

NOTE: GLASS BEAD BED MATERIAL NOMINAL DIAMETER = 280 μm

a) HEAT TRANSFER COEFFICIENT

b) NUSSELT NUMBER