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A NEW METHOD TO INTENSIFY HEAT TRANSFER OF AN FCC CATALYST COOLER: EXPERIMENTAL VALIDATION

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ABSTRACT

In this study, a cold-model fluidized bed exchanger with similar geometry and heat exchange mechanism as industrial resid FCC catalyst coolers was studied systematically to find optimized operating conditions and geometrical structure. A heat transfer intensification method with promoted solids mixing by utilizing an internally circulating fluidized bed was proposed and tested. Higher heat transfer coefficients were obtained and better performances were partially validated.

INTRODUCTION

In a modern petroleum refinery, a catalyst cooler is an indispensable device in a fluid catalytic cracking unit processing heavy resid feedstock (i.e. RFCC unit). (1-2) Due to higher coke yield, superfluous heat is released during catalyst regeneration exceeding the requirement for unit heat balance. The function of a catalyst cooler is to remove the superfluous heat by contacting high-temperature catalyst particles with heat transfer tubes with flowing liquid water in a fluidized bed to produce valuable steam.

Due to higher reliability and better operating flexibility, fluidized bed heat exchangers placed outside the regenerator named as external catalyst coolers are usually preferred choices for RFCC unit designs in recent decades. In most external catalyst coolers, heat exchange happens between vertical tube bundles and fluidized FCC particles. In China's most RFCC catalyst coolers, heat tube is designed as an independent heat exchange unit which can be switched off when leakage failures happen due to various damages. This is to prolong the unit turnover period by reducing the shut-down frequency of the entire unit.

In essence, a FCC external catalyst cooler is a fluidized bed with multiple vertical tube internals. Heat exchange properties are closely related to the bed hydrodynamics. However, problems such as low heat transfer capacity, unstable catalyst circulation and tube damages were frequently reported in industrial catalyst coolers. (3-5) When these incidents happen, unit throughput has to be reduced due to the cooling bottleneck. Sometimes, the entire unit has to be shut down, resulting in serious economic loss. This demonstrates that optimized catalyst cooler design based on deep understanding of the heat transfer properties and its related hydrodynamics is still not reached currently.

In this study, a cold-model fluidized bed exchanger with similar geometry and heat exchange mechanism as industrial FCC catalyst coolers was built to study its heat transfer properties. A new method to increase its bed-to-wall heat transfer coefficient was proposed and partly validated experimentally. The obtained understandings are also helpful in optimizing the design and operation of current industrial FCC catalyst coolers.

EXPERIMENTAL SETUP

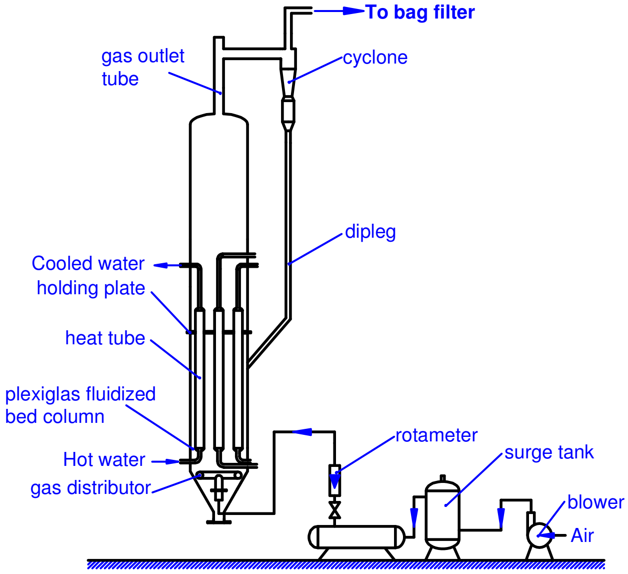


Figure 1 Schematic diagram of the experimental unit

(a) catalyst cooler (b) finned heat tubes

Figure 2 Pictures of the catalyst cooler and finned heat tubes

In order to simulate an industrial FCC catalyst cooler, a large-scale cold model as shown as in Figure 1 was established. The heart of this unit is a cylindrical fluidized bed of I. D. 0.5 m and height 3 m. Its transparent plexiglas wall made visual observation of the inner flow behavior possible. Compressed air from a Roots blower was fluidizing gas and FCC equilibrium catalyst of mean diameter 69.4 μm and particle density 1500 kg/m^3 was the fluidized particles. A cyclone installed above the bed captured the entrained particles in the outflow gas and return them through its dipleg to the dense bed to maintain a constant particle inventory.

Nine vertical steel finned heat tubes of height 1.2 m, similar geometry as in industrial units as shown in Figure 2, were used in this study. The outer diameter of the heat tube was 76 mm. Ten fins of width 10 mm and thickness 2 mm were welded around each tube. There were two finned sections of height 0.5 m on the top and bottom of each heat tube. There was one tube set in the bed center and eight tubes around a concentric circle of diameter 334 mm. Similar hydraulic diameter was maintained in the designs of the experimental unit and industrial catalyst coolers. In most experimental runs, the static bed height was 1.45 m to guarantee all heat tubes buried in the dense bed. Superficial gas velocity ranged from 0.05 m/s to 0.65 m/s, including a bubbling and a turbulent flow regimes.

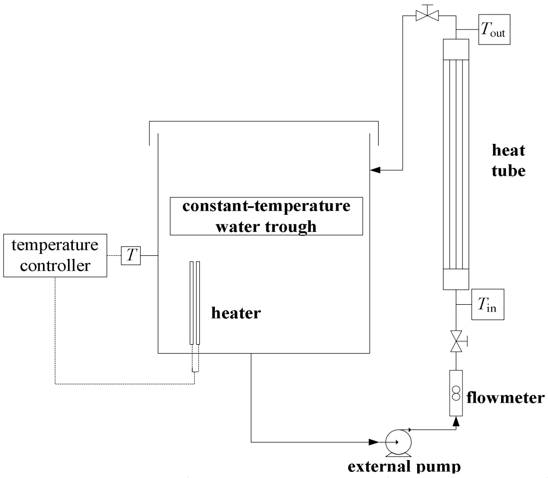


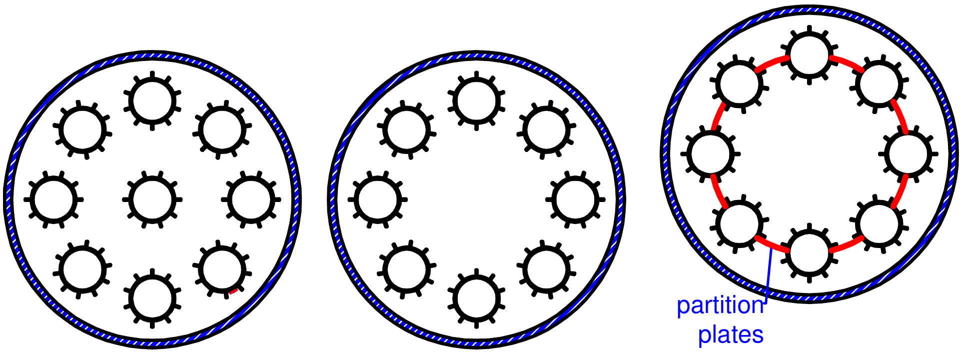
Figure 3 Schematic diagram for determination of the heat transfer coefficient

In this study, the most important measurement parameter was the bed-to-wall heat transfer coefficient. A similar heat transfer mechanism as in industrial catalyst coolers was employed to measure the bed-to-wall heat transfer coefficient as shown in Figure 3. Hot water from a constant-temperature trough, usually in the range of 70~90 °C, was pumped into the heat tubes of the catalyst cooler. After contacting with cold particles in the fluidized bed, water flowing out of the heat tubes was cooled down and then flowed into the trough to recover its lost heat. With water inlet and outlet temperatures (T_{in}, T_{out}), average tube wall temperature ($\overline{T_w}$) and bed temperature ($\overline{T_b}$) known, the bed-to-wall heat transfer coefficient h can be calculated by the following heat balance equation:

$$Cm\left(T_{in} - T_{out}\right) = hA_w\left(\overline{T_w} - \overline{T_b}\right) \quad (1)$$

Here, C is the specific heat of water, m is the water mass flow rate and A_w is the heat transfer area. Here, only tube outer surface was counted without including fin surfaces. According to previous studies, (6-7) the measured heat transfer coefficient includes the contributions of gas and solids convections. This is similar as in industrial catalyst cooler where the operating temperature is usually below 650 °C and heat transfer by radiation is negligible. However, heat transfer directions in this study and industrial catalyst coolers are opposite. In this study, heat is transferred from hot water in the tube to outside cold particles. In industrial catalyst coolers, heat is transferred from hot fluidized particles to low temperature water flowing in the tubes.

Three types of catalyst cooler were used in this study, whose lateral arrangements of the heat tubes are shown in Figure 4. The first one was a similar design as most industrial dense-bed catalyst cooler where only an annular pipe gas distributor was used below heat tubes. We call this one the base catalyst cooler (BCC) in this study. There were 36 holes of diameter 10 mm in this pipe distributor, corresponding to an open area ratio of 1.5%.



(a) BCC (b) ACC-1 (c) ACC-2

Figure 4 Heat tube arrangements in the three types of catalyst cooler

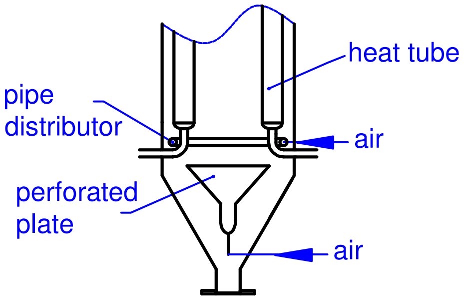


Figure 5 Gas distributors in annular catalyst coolers

In order to test our idea to intensify heat transfer in FCC catalyst coolers, the annular pipe gas distributor was revamped as in Figure 5. There were a central perforated plate distributor and an above annular pipe distributor. The idea of this design is to provide non-uniform gas distribution to promote inner solids circulation. At a constant gas flow rate, the bed-to-wall heat transfer coefficient is expected to increase due to stronger solids mixing. Moreover, the adjustable range of its cooling capacity can be increased by changing the gas flowrate ratio through the two gas distributors. Thus, more operating flexibility is provided. The diameter of the central plate distributor was 320 mm. More gas flowed through it. Less gas flows through the annular pipe distributor. Its function was mainly to aerate the down-flowing solids. This is the annular catalyst cooler (ACC) we proposed to intensify bed-to-wall heat transfer. As seen in Figures 4(b) and 4(c), the central heat tube was removed in the ACC to avoid interfere on solids flow. Later, in order to further promote solids circulation, vertical partitions plates were installed to make the annular heat tubes a close circle as shown in Figure 4(c). In this study, the two types of catalyst cooler were named as ACC-1 and ACC-2, respectively.

RESULTS AND DISCUSSION

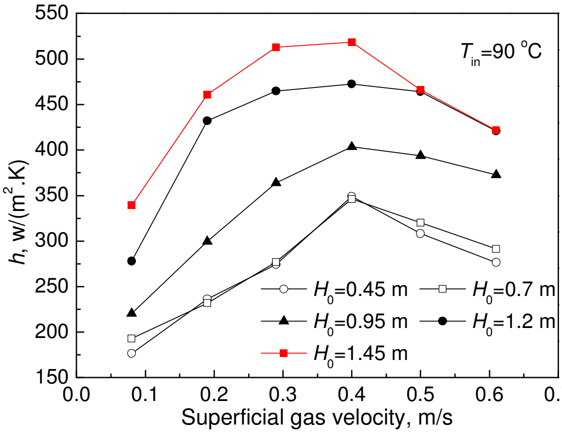


Figure 6 Effect of static bed height on bed-to-wall heat transfer coefficient of BCC

Figure 6 depicts the measured bed-to-wall heat transfer coefficients under different superficial gas velocities and static bed heights (denoted as H_0). When heat tubes are buried in the dense bed, *h* first increases and then decreases with increasing gas velocity, peaking at u_0 =0.4 m/s. If the cross section area occupied by the heat tubes is subtracted, the actual transitional gas velocity is approximately equal to the onset turbulent fluidization velocity computed by the correlation of Cai et al. (8). The trend and value range are generally agreeable with other studies, (9-10) demonstrating the reliability of the measurement in this study. Moreover, as static bed height decreases, *h* decreases constantly. However, under all static bed heights, the change of *h* follows a same trend with gas velocity, demonstrating the dominant influencing role of the dense bed.

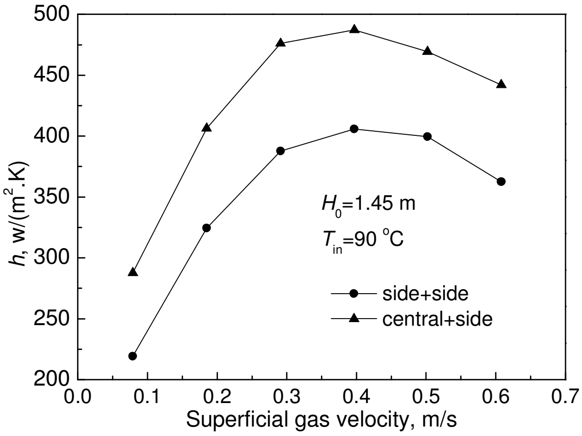
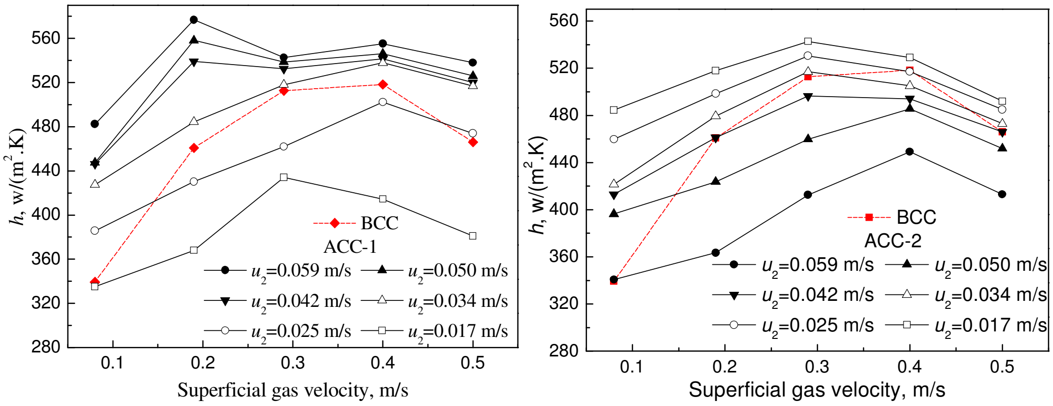


Figure 7 Effect of radial position on bed-to-wall heat transfer coefficient in BCC

Figure 7 shows the effect of radial positions on *h*. Due to limits of experimental designs, the *h* of the central heat tube could not be measured directly. The measured *h*s shown in Figure 7 are actually the averaged value of two heat tubes.

As seen in Figure 7, the *h* of the central heat tube is clearly higher than that of the side tube. Despite of lower solids fractions, higher solids renewal frequency on the surfaces of the central tube plays a dominant role in its higher *h*s. Moreover, this demonstrates that weaker wall effect is favorable to good heat transfer performance.



(a) ACC-1 (b) ACC-2

Figure 8 Bed-to-wall heat transfer coefficients of ACC-1 and ACC-2

Figure 8 shows the performance of the annular catalyst coolers in this study. It is noted that u_2 in Figure 8 is defined as the gas volume flow rate of the pipe distributor divided by the whole column cross-sectional area. Generally, ACC's intensification effect can be observed in most operating conditions as seen the higher *h*s for both ACC-1 and ACC-2. Generally, as gas flow rate from the pipe distributor increases, *h*s of both ACC-1 and ACC-2 increase under all superficial gas velocities. When u_2 is very low, there are some cases that ACC's *h*s are lower than the corresponding *h*s in BCC. Very likely, bad fluidization states exist near the column wall under these operating conditions, resulting in the poor heat transfer performance. When u_2 exceeds 0.042 m/s, it seems from Figure 8(a) that a double peak trend exists in the *h vs.* u_0 curves. The highest *h*s appear at u_0 =0.2 m/s, far smaller than in BCC. However, there is no double-peak trend in all *h vs.* u_0 curves of ACC-2. The transitional gas velocity of ACC-2 appears at u_0 =0.3 m/s, also smaller than in BCC.

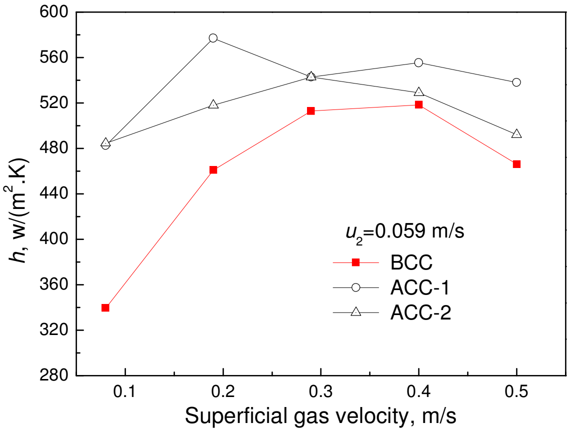


Figure 9 Comparison of the highest *h*s in the three types of catalyst cooler

Figure 9 compares the best heat transfer performance of the three types of catalyst cooler, which enables the intensification effect of the annular catalyst coolers more clearly observed. For the maximum *h*s, ACC-1 and ACC-2 are 11.3% and 4.7% higher than BCC, respectively. Otherwise, the smaller transitional gas velocities in ACC-1 and ACC-2 also indicate smaller fluidizing gas usage and potential energy saving in industrial units.

In an objective analysis, except for the intensification effect, the improved heat transfer performance in ACC coolers may also originate from their improved gas distribution. After all, the single pipe distributor in BCC can not realize same gas distribution in ACCs. Moreover, it is a little unexpected that the performance of ACC-2 is inferior to ACC-1. In view of the wall effect shown in Figure 7, this may be due to the stronger wall effect in ACC-2. It can thus be expected that the hydraulic diameter and fin arrangement should be further optimized to achieve better heat transfer performance in industrial catalyst cooler designs.

CONCLUSIONS

After above-mentioned experimental studies, at least the following conclusions can be drawn:

(1) The intensification heat transfer effects of the annular catalyst cooler is partilly validated. Higher bed-to-wall heat transfer coefficient, smaller fluidizing gas usage and higher adjustable flexibility are realizable in annular catalyst coolers.

(2) To achieve good heat transfer performance in FCC catalyst coolers, uniform gas distribution, limited wall effect, good fluidization state are neccessary. Cautions should be taken with regard to the selection of appropriate hydraulic diameter and fin arrangements.

(3) An optimized gas velocity range of 0.3~0.5 m/s is recommended for regular dense-bed FCC catalyst cooler design.

NOTATION

A_w	heat transfer area	m^2
C	specific heat of water	J/kg
h	bed-to-wall heat transfer coefficient	$w/(m^2.K)$
H_0	static bed height	m
m	water mass flow rate	kg/s
T_b	bed temperature	^oC
T_{in}	water inlet temperature	^oC

T_{out}	water outlet temperature	^oC
T_w	wall temperature of heat tube	^oC
u_0	superficial gas velocity	m/s
u_2	gas volume flowrate from the pipe distributor of the ACC coolers divided by the bed cross-sectional area	m/s

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