

# FCC Catalyst Coolers Open Window to Increased Propylene

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## **Abstract**

The market demand for propylene has brought a strong emphasis onto many FCC units to run in maximum propylene mode. Increasing reactor temperatures in pursuit of higher propylene, without regenerator heat removal, can raise the regenerator temperature to unacceptable levels resulting in accelerated catalyst deactivation, degraded cracking selectivity and a need for exotic mechanical design to avoid equipment damage.

This paper presents FCC modeling that demonstrates the utility of continuous heat removal from the regenerator for maximum propylene operations. Developments in FCC catalyst cooling technology have given the refiners a flexible and reliable option to confront the heat balance challenges of maximum propylene FCC operations.

### **Introduction**

In an unconstrained environment, increasing FCC propylene production can be as easy as just increasing the reactor temperature. However in most cases increasing propylene yield is not that easy as most FCC units are already operating against several physical and economic constraints. More commonly, regenerator coke burning and vapor recovery unit capacity limit increasing reactor temperature without first reducing FCC feed rate.

In grassroots FCC installations, coke burning and vapor recovery capacity can be built into the unit design and existing FCC units can be revamped to include the requisite coke burning and vapor recovery capacity for increasing propylene production. However:

- Even with abundant coke burning and vapor recovery unit capacity, high regenerator temperature can emerge as a major constraint to increasing reactor temperature because of the impact of the higher temperature on the unit heat balance<sup>1</sup>.
- FCC operators can effect a reduction in equilibrium catalyst activity to offset the increasing regenerator temperature that would naturally come from increasing reactor temperature, but reducing catalyst activity runs counter to the more basic objective of increasing propylene production.

### **History of FCC Propylene Production**

The first commercial FCC unit was built by The M.W. Kellogg Company in Standard Oil of New Jersey's Baton Rouge, Louisiana refinery and commissioned in May 1942. Between 1942 and 1944 Kellogg built 22 of 34 FCC units constructed throughout the U.S, and the FCC process quickly became a major contributor to worldwide propylene and butylene production.

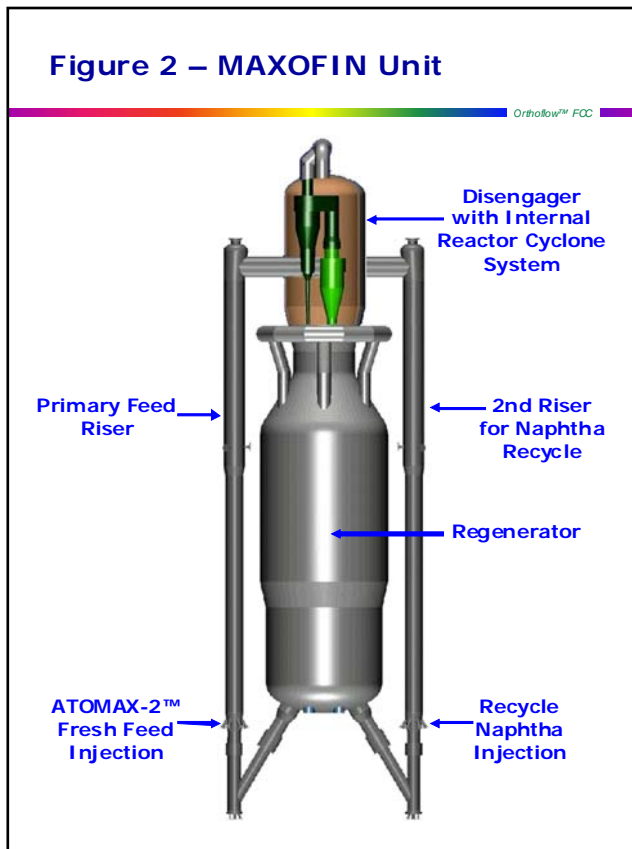
Rare Earth exchanged Y zeolite catalyst was first synthesized by Mobil in 1959. By the late 1960's, over 90% of U.S. FCC units were operating with the Mobil invented zeolite catalyst. The high activity of the zeolite catalysts, compared to the earlier amorphous catalysts, greatly improved gasoline yield and reduced coke and dry gas yields from the FCC units, but the catalyst's high hydrogen transfer characteristic greatly reduced light olefin yield and gasoline octane<sup>1</sup>.

In the 1970's after introduction of zeolite catalyst, FCC unit design and operation evolved to regain some of the lost octane and light olefin yield, primarily with higher reactor operating temperature and riser cracking<sup>2</sup>. Increasing reactor temperatures increased light olefin yield, but this came at the expense of increased yield of dry gas, a lower value FCC product.

During the 1980's Mobil introduced two new technologies with application to increasing the production of light olefins and octane while limiting incremental dry gas production: (1) Mobil developed ZSM-5 catalyst additive to crack low octane (linear) gasoline boiling range olefins and paraffins into light olefins, and (2) Mobil invented Closed Cyclones which minimize product vapor residence time between the riser outlet and the main fractionator<sup>3, 4</sup>.

In addition to the reduction in dry gas, the Closed Cyclone riser termination system also reduced delta coke, especially on units that previously employed low catalyst separation efficiency riser termination devices. Therefore, the Closed Cyclone system was especially adept at increasing FCC propylene production because it simultaneously relieved constraints of both vapor recovery unit capacity and regenerator operating temperature.

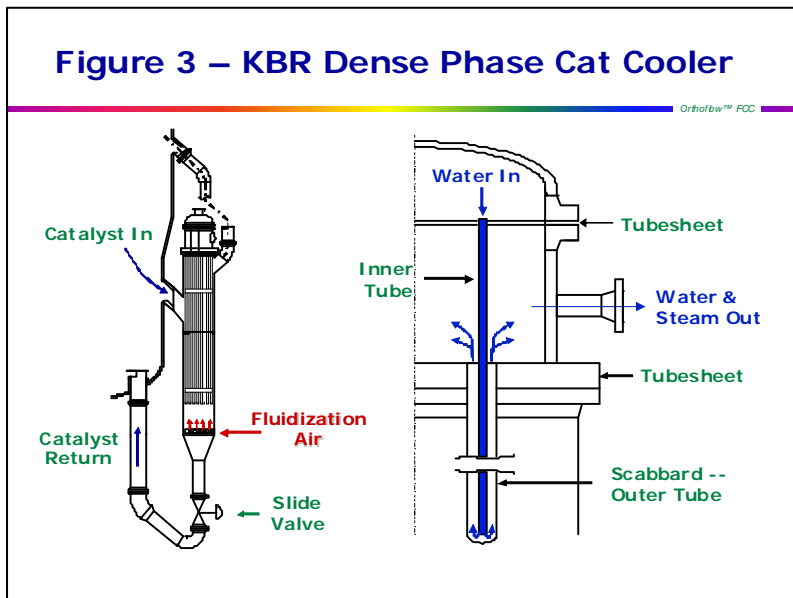
The MAXOFIN™ FCC Process introduced by M.W. Kellogg and Mobil in 1998<sup>5</sup> depicted in Figure 2 is designed to maximize the production of propylene, ethylene, and aromatics from traditional FCC feedstocks by combining the effects of FCC catalyst, ZSM-5 additive and a high severity second riser designed to crack surplus naphtha and C4's into incremental light olefins and aromatic naphtha<sup>6</sup>. Like closed cyclones, the MAXOFIN FCC Process also provides some relief to the heat balance while operating at high reactor temperatures because of the limited delta coke from re cracking the recycled naphtha and C4 feedstocks. The recycled naphtha and C4's essentially serve as a regenerator refrigeration system while simultaneously serving to increase propylene production in the high severity second riser.



**KBR Dense Phase Catalyst Cooler**

For many decades and until recently, FCC catalyst coolers have been considered only as a means to effectively process high carbon residue FCC feedstocks where the impact of Conradson Carbon Residue (CCR) on delta coke is a fundamental driver of the FCC heat balance.

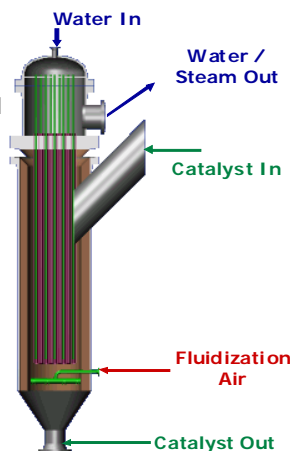
CCR in the feed increases the amount of coke deposited on the catalyst as it passes through the riser. The increased concentration of coke on the catalyst as it passes through the reactor is referred to as “Delta



Coke". Without intervention, increasing delta coke leads to high regenerator temperature, reducing FCC feed conversion due to lowering of the catalyst to oil ratio and accelerated catalyst deactivation. To mitigate the impact of increasing feed CCR on regenerator temperature, the heat released during catalyst regeneration must be controlled or heat must be removed from the system. The best option for controlling the heat balance with increasing delta coke is often the use of a catalyst cooler and/or regenerator operation in partial CO combustion mode.

Figure 4 – Key Features of Catalyst Cooler

- ◆ High heat transfer coefficient
- ◆ Flow-through design, high mean temperature differential
- ◆ No fluidization impingement on tubes
- ◆ Upflow boiling with natural boiler feed water circulation
- ◆ Tube bundle easily removed
- ◆ High turndown capability
- ◆ Commercially proven design



The KBR dense phase catalyst cooler depicted in Figure 3 was commercialized in 1991 based on extensive KBR experience in high temperature ammonia applications and cold flow modeling of the catalyst side at KBR's Houston Technology Development Center<sup>1</sup>. Two distinguishing features of the KBR dense phase catalyst coolers impart flexibility in heat removal duty and resistance to tube failure from erosion by the catalyst. The first feature is a gas vent line at the top of the cooler fluid bed that prevents catalyst backmixing

between cooler and regenerator whenever the cooler catalyst circulation is stopped, thereby providing complete heat removal turndown capability. Without the vent, cold flow modeling has demonstrated that backmixing between the cooler and regenerator (and therefore heat transfer in a commercial unit) will occur due to fluidization of catalyst in the inlet duct by aeration gas traveling from the cooler back into the regenerator bed. With the vent in place, cooler aeration gas returns to the regenerator through the vent rather than through the catalyst inlet duct, allowing catalyst in the inlet duct to defluidize whenever catalyst circulation is stopped. The other distinguishing feature of the KBR dense phase catalyst cooler design is that the tubesheet is located above the tubes, which has several important ramifications:

- ✓ Downward hanging tubes allows the cooler shell fluidization air to be introduced well below the tubes, preventing any possibility of cooler fluidization air jet impingement on the tubes which could cause an erosion related tube failure.
- ✓ Because steam is generated in upflow between the inner and outer tubes, the cooler can utilize natural boiler feed water circulation, eliminating the need for forced boiler feed water circulation pumps along with their associated cost and reliability issues.
- ✓ The orientation of the tube bundle also facilitates maintenance and inspection of the cooler because the tube bundle can be pulled from the top of shell.

There are now sixteen KBR dense phase catalyst coolers in operation, and there have been no reports of erosion related tube failure in any of these installations.

**Use of Catalyst Cooler for Propylene production**

Increasing reactor temperatures in pursuit of higher propylene increases regenerator bed temperature and, without regenerator heat removal, raises this temperature to unacceptable levels resulting in accelerated catalyst deactivation, degraded cracking selectivity and a need for exotic mechanical design to avoid equipment damage.

**Figure 5 – Feedstock Properties**

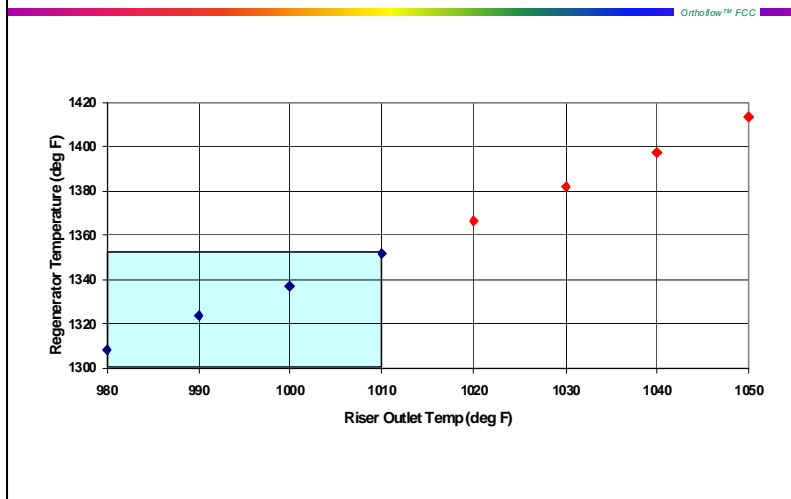
Feedrate, BPSD	40,000
° API	28.00
Molecular Weight	445
Sulfur, wt%	0.05
Total Nitrogen, ppmw	2
Watson K	12.27
Conradson Carbon, wt%	0.20
Distillation type D2887, °F	
10%	700
30%	754
50%	804
70%	883
90%	997

The utility of FCC regenerator heat removal for maximizing propylene production is demonstrated by way of a hypothetical example using KBR’s proprietary FCC yield modeling software. The base case for the exercise is a hypothetical 40,000 BPSD FCC operation on a good quality hydrotreated VGO feedstock. A summary of the base case feedstock quality is presented in Figure 5. The study cases are based on a catalyst activity of 72 and a constant feed preheat temperature of 650 deg F.

As shown in Figure 6, while operating at the base case 980 deg. F riser outlet temperature, the regenerator temperature heat balances at about 1310 deg. F, a temperature which is considered very compatible with good FCC catalyst activity maintenance and minimal generation of dry gas and other thermal cracking products in the feed injection zone. As would be expected based upon the basic tenants of the FCC heat balance, the regenerator heat balanced temperature increases with increasing riser outlet temperature.

For the sake of this example, considering the deleterious impact of regenerator temperature on catalyst activity, product yield selectivity and mechanical reliability, the regenerator bed temperature will be limited to a maximum of 1350 deg. F. As can be seen in Figure 6, the maximum allowable riser outlet temperature will be approximately 1010 deg. F when limiting the regenerator temperature to 1350 deg F.

**Figure 6 – Impact of ROT on Regenerator Temperature (w/o Cat Cooler)**



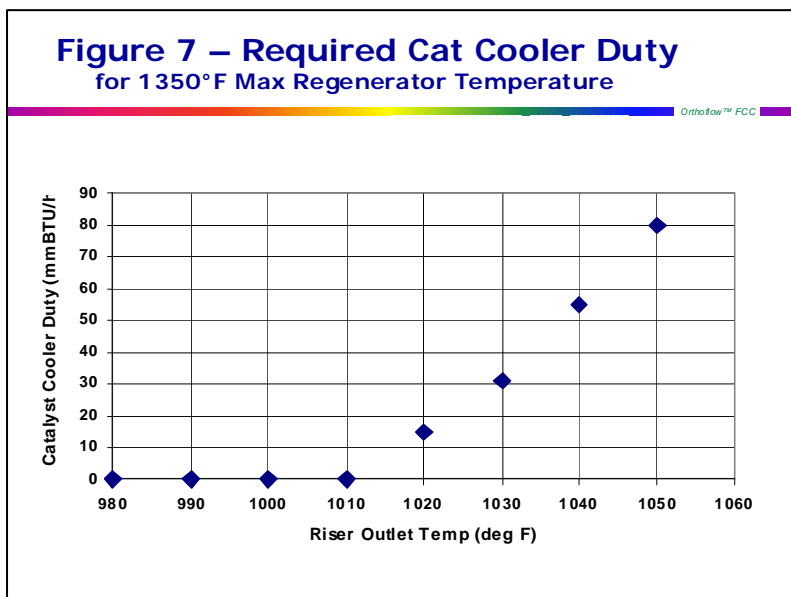
The increasing regenerator temperature is primarily driven by the increasing temperature of

the spent catalyst being returned to the regenerator

Utilizing a variable duty dense phase catalyst cooler, it is possible to keep the regenerator temperature from exceeding 1350 deg. F at riser outlet temperatures exceeding the 1010 deg. F value. For purposes of this example, the riser outlet temperature is increased to as high as 1050 deg. F. Figure 7 shows the catalyst cooler duty required to maintain the regenerator bed temperature of 1350 deg F at riser outlet temperatures greater than 1010 deg F.

The point of this exercise is shown in Figure 8 which shows that starting from a base case propylene yield just below 9.0 vol%, the propylene yield can only be increased to about 10.5 vol% without the use of regenerator

heat removal while honoring the 1350 deg F regenerator temperature constraint. It also shows that the propylene yield can be increased to as high as 13.5 vol% while using the catalyst cooler to control the regenerator temperature.



Deactivation of FCC catalyst occurs by various mechanisms. One of the primary modes of FCC catalyst deactivation is hydrothermal deactivation caused by exposure of catalyst to high regenerator temperatures in the presence of water vapor. Figure 9 indicates the expected increase in regenerator temperature and decrease in catalyst activity in the present example at constant fresh catalyst addition rate assuming a catalyst cooler is not utilized. As explained before, high riser outlet temperature results in a high regenerator temperature, which accelerates the catalyst deactivation.

One of the conclusions that can be drawn from this study is that a refiner might want to invest in an FCC catalyst cooler if a large investment is being made to increase FCC coke burning and vapor recovery unit capacity for the purpose of increasing propylene production.

Figure 8 – Impact of ROT on Propylene

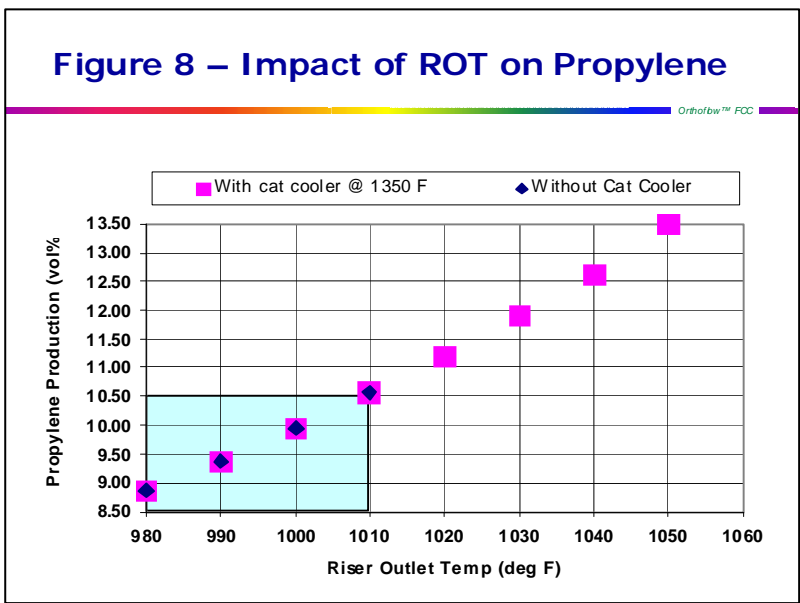
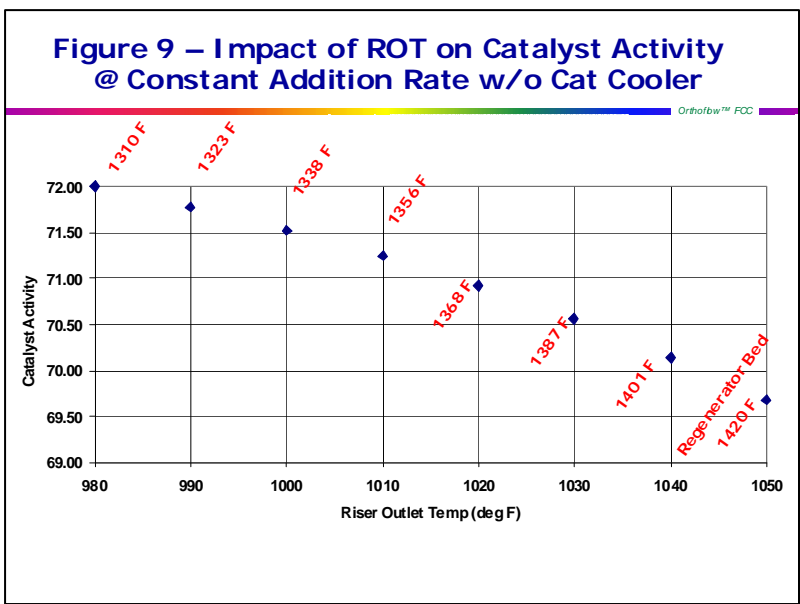


Figure 9 – Impact of ROT on Catalyst Activity @ Constant Addition Rate w/o Cat Cooler



## History of Catalyst Coolers

The early FCC catalysts produced coke yields as high as 12 wt %. This resulted in a reactor-regenerator system where the amount of heat liberated by coke combustion was more than what could be removed by the process streams. In 1942, M.W.Kellogg introduced "Recycle Catalyst Coolers" on a Kellogg Model II FCC units to solve this heat balance issue.

By 1948, there were twenty two (22) commercial Recycle Catalyst Coolers in operation. Most of these coolers had 988, 1 ½" O.D. tubes, which were 22 ft long. The design duties of these coolers were as high as 100 million BTU/hr each. These coolers had catalyst at 25 ft/s moving through the tubes transferring heat to water/steam in the shell. A catalyst standpipe withdrew catalyst from the bottom of the regenerator bed that was conveyed upwards through the cooler tubes at high velocity. The cat cooler duty was varied by adjusting the catalyst circulation rate with a slide valve.

These early catalyst coolers were mechanically complex, with large expansion joints in the shell to accommodate the difference between the inlet channels/tubes and the shell. The problems encountered in these coolers were mainly related to erosion due to internal solids mixing which included:

### Fundamentals of Fluid Bed to Tube Heat Transfer

The basic science of heat transfer between a fluidized bed and a confining wall was described by Chin-Yung Wen and Max Leva in a 1956 paper<sup>7</sup>.

- For a fluidized bed confined in a pipe, there will always be a laminar fluid film in immediate contact with the pipe. The heat transfer mechanism from the pipe wall to the laminar flow is via conduction, and this constitutes the major resistance between the fluid bed and the pipe wall.
- The heat transfer from the laminar film to an adjacent buffer layer is through turbulent mixing due to the eddy movement of the fluid.
- From the boundary layer to the core of the fluid bed, the prevalent heat transfer mechanism is by turbulent mixing of the solid particles
- The higher the thickness (or width) of the laminar layer, higher will be the resistance for heat transfer from tube walls to the flowing fluid. Therefore, up to a point, an increase in velocity of the fluid in the bed that decreases the laminar layer thickness will leads to an increase in heat transfer coefficient.
- As the velocity of the fluid in the bed is increased further, the heat transfer increases to a "max heat transfer" value beyond which, it decreases with velocity. This is because; the bed expands with higher gas flow and increases the solid particle spacing, reducing the rate of heat transfer via turbulent mixing of the particles.

- Erosion of Cooler Outlet Cone Transition
- Erosion of Tubes and Tube Sheets at the cooler inlet
- Failure of linings in the standpipes and carrier lines
- Erosion of the carrier line at the air/catalyst mixing point.

The run lengths obtained with these dilute phase cooler were typically three to four months, at the end of which tube bundle repair or replacement was required. As the flowing catalyst was in dilute phase (density ~ 3 lb/ft<sup>3</sup>), the heat transfer coefficient was relatively low. Danzinger<sup>3</sup> from an analysis of commercial cat cooler data showed the heat transfer coefficient ranges from 9 – 35 BTU / hr ft<sup>2</sup> °F, with most of the coefficients falling between 18 and 34. Beginning of 1950, cracking catalyst with better coke selectivities became available, and these catalyst coolers were no longer used.

**Mixtures in Vertical Transport**

In a 1963 paper, W. J. Danzinger presented the development of a heat transfer coefficient correlation for a fluidized catalyst bed moving vertically based on commercial data from a 1940's vintage FCC recycle catalyst cooler designed by M.W. Kellogg<sup>8</sup>. The reported study was conducted for a recycle catalyst cooler operating in dilute phase as well as dense phase.

- A correlation of the heat transfer coefficients of air-fluidized cracking catalyst of about 50-micron average particle diameter in vertical transport is presented. The correlation, based on commercial data for cooling and the data of Ferber and Morley<sup>9</sup> for heating, is;

$$(h \cdot d/k) = 0.0784 * ((D \cdot G)/\mu)^{0.68} * (W_a/W_g)^{0.45}$$

The correlation covers Reynolds numbers from 178 to 25,400, solids-to-gas weight ratios of 2 to 446, and tube I.D. from 0.689 to 1.497 inches

- Data were obtained on recycle catalyst coolers of two designs, both of vertical, single-tube pass, removable-bundle, fire-tube boilers with the air-catalyst mixture flowing upward through the tubes. The steam drum was elevated sufficiently to limit vaporization in the boiler shell to about 10% of the thermosyphon water flow. In one design, the single-section cooler tube bundle contained 988 steel tubes, 1½ - inch O.D. by 22 feet long. The second design provided two sections in parallel, each bundle containing 580 steel tubes, 1 7/8-inch O.D. by 19 feet long.
- The arrangement and typical instrumentation is shown in Figure 10. Catalyst flow was controlled by a slide valve, which was positioned by a temperature element in the regenerator bed.
- Figure 11 shows the variation of heat transfer coefficient with Reynolds number.

The advent of resid cracking in the early 60's paved the way to regenerator bed coils. The first residue cracker built in 1960, for Phillips Petroleum had 15 layers of horizontal hairpin coils which covered 320 degrees of the vessel circumference near the wall of the regenerator. The high pressure steam for use in the refinery was generated by passing boiler feed water through the coils. In the original design of these bed coils, a heat transfer coefficient of 60 BTU/hr ft<sup>2</sup> °F was used<sup>1</sup> however this proved to be conservative and the steam generated was greater than expected. This high heat transfer coefficient was the result of the coils immersed in a relatively high density (25 to 35 lb/ft<sup>3</sup>) fluidized bed in the regenerator. Unlike the dilute phase, the low velocity in the regenerator (2 to 3 ft/s) resulted in a lower erosion of the coils.

The main problem encountered by the regenerator coils was on the inside (water) side. The use of low quality boiler feed water resulted in a mineral deposition and eventually failure due to pitting. Also, the low velocity in the coils resulted in a slug or stratified flow ultimately leading to

failure due to thermal stresses. To avoid this problem, the flow inside the tube was maintained in the bubble flow regime, restricting the flexibility of these coolers to cope with changes in feed rate and feed quality.

The research continued for a catalyst cooler which was more flexible, and operates with low catalyst velocity to avoid the erosion which compromised the dilute phase coolers. In 1991, this resulted in the modern day KBR Dense Phase Catalyst Cooler with water and steam on the tube side and hot slow moving catalyst on the shell side. As stated previously, there are sixteen KBR dense phase catalyst coolers in operation, and there have been no reports of erosion related tube failure in any of these installations.

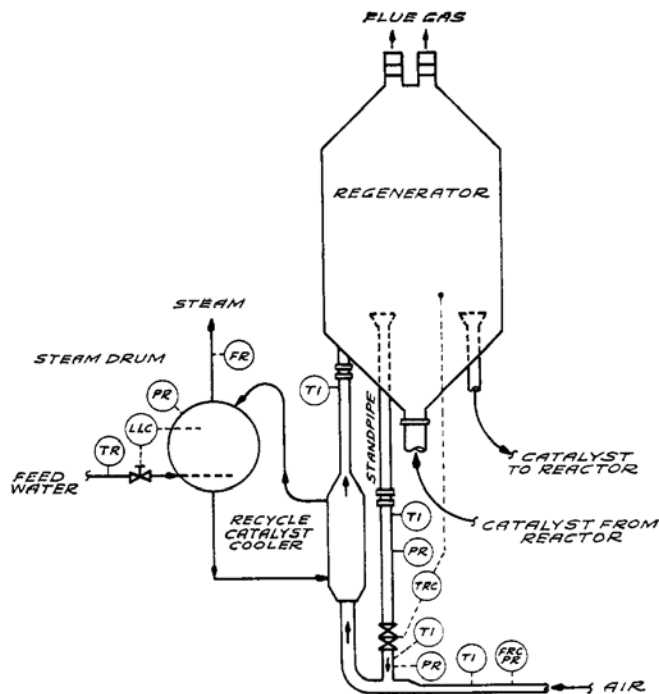


Figure 10: Arrangement and instrumentation of recycle catalyst cooler

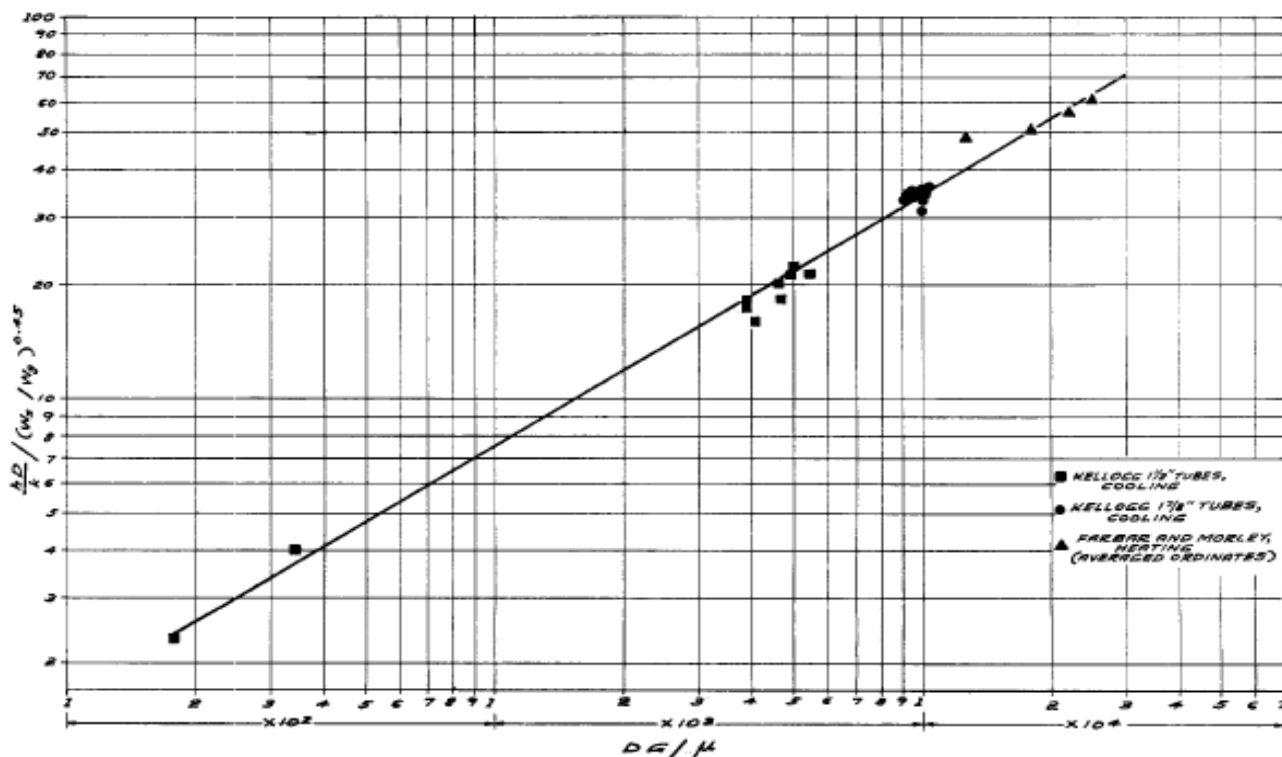


Figure 11: Correlation of data on heat transfer of air-cracking catalyst mixtures in vertical upward transport

### **Conclusions**

A refiner should consider investing in an FCC catalyst cooler if a large investment is being made to increase FCC coke burning and vapor recovery unit capacity for the purpose of increasing propylene production. Investing in coke burning and vapor recovery expansion without a catalyst cooler will usually result in a cat cracker that is all dressed up but having no where to go.

Once a decision is taken to install an FCC catalyst cooler, careful consideration should be given to aspects of the cooler technology that impact the cooler's operating flexibility and on-stream reliability.

### **References**

1. Johnson, T.E., "Improve Regenerator Heat Removal," Hydrocarbon Publishing, pp: 55-57, November 1991
2. E.L. Whittington, J.R. Murphy and I.H. Lutz, "Catalytic Cracking – Modern Designs, Symposium on Advances in Gasoline Technology, Presented before the Division of Petroleum Chemistry, Inc, American Chemical Society New York Meeting, August 27 – September 1, 1972
3. C.D. Andersen, F.G. Dwyer, G. Koch, P. Niiranen; 9th Ibero American Symp. Catal.; Lisbon, Portugal; 1984.
4. Miller, R. B., Johnson, T. E., Santner, C. R., Avidan, A. A., Johnson, D. L., "FCC Reactor Product – Catalyst Separation – Ten Years of Commercial Experience with Closed Cyclones", 1995 NPRA Meeting.
5. Miller, R.B., Niccum, P.K., Claude, A., Silverman, M.A., Bhole, N.A., Chitnis, G.K., McCarthy, S.J. and Liu, K., "MAXOFIN™: A Novel FCC Process for Maximizing Light Olefins Using a New Generation ZSM-5 Additive," 1998 NPRA Meeting, March 1998.
6. Niccum, P. K., Gilbert, M. F., Tallman, M.J. and Santner, C. R., "Future Refinery -- FCC's Role in Refinery / Petrochemical Integration," 2001 NPRA Meeting, March 2001
7. Wen, C. Y. and Leva, M., "Fluidized-bed Heat Transfer: A Generalized Dense-Phase Correlation," A.I.Ch.E. Journal, December 1956, pp: 482-488
8. Danzinger, W. J., "Heat Transfer to Fluidized Gas-Solids Mixtures in Vertical Transport," I&EC Process Design and Development. 2. pp 269-276, 1963
9. Farbar, L. and Morley, M. J., "Heat Transfer to Flowing Gas-Solid Mixtures in a Circular Tube," Ind. Eng. Chem., 1957, 49(7), 1143-1150