AGITATED VESSEL HEAT TRANSFER DESIGN

By Frederick Bondy

There has been continued growth of refinery-based downstream processing involving petrochemicals, polymers and specialty chemicals such as lube oil additives, high impact, crystal and expandable polystyrenes, certain synthetic fibers, vat dyes, wire enamels, automotive/ airplane plastics, etc. Therefore, the ability to design for types of equipment not typically associated with refinery units is now considered to be a useful tool for the hydrocarbon processing engineer. Such a design area involves heat transfer in agitated vessels such as Continuous Stirred Tank Reactors (CSTRs) or in Batch Operations.

This article provides an outline of simple procedures to achieve heat transfer design wherein heat transfer coefficients, heat transfer areas for jackets and coils and the pressure drops within them, as well as batch heatup/cooldown times, can be determined.

In an agitated vessel, for a given jacket fluid, heat transfer depends on the type of external jacketing or coils being used, as well as the agitator. The processing and nature of the reaction material typically determines the type of agitator. Many types of agitators are available such as turbine types (curved-blades, flat-blades, retreating blades), propellers, pitched flat-blades, helical ribbons, and anchors.

Heat transfer through jackets, coils or the tubes of simple S&T exchangers follows the standard relationship: $Q = UA$ (delta T), where the Overall Heat Transfer Coefficient (U) is determined from a series of five resistances involving inside/outside film coefficients, inside/outside fouling factors and the metal thickness/thermal conductivity term.

For coils inside a vessel, the U-value must be referred to either the inside or outside coil diameter, as with heat exchanger tubes, due to the large difference between inside and outside coil areas. The mean coil diameter should also be used to adjust the metal/thermal conductivity term.

For continuous operation under isothermal conditions, $Q = UA$ (delta T) can be applied directly. If the inlet and outlet temperatures of the jacket medium are different, then $Q = UA$ (delta T, log mean) must be used.

Work Highlights

Process, Operations & Safety

Provided technical support regarding gas treating unit troubleshooting and consultation to assist in resolution of solution fouling, reclaiming and contamination issues.

Completed a design basis memorandum for a wastewater treatment upgrade for a Mediterranean refiner. This will significantly increase flexibility and processing capability, while providing for a phased implementation of new facilities. After initial review, the client expanded the DBM scope to include additional provisions.

Providing a number of hydrotreating unit performance modeling and revamp screening assessments for a major licensor.

For batch operation heating, the below equation can be used:

$$\ln\{(T - t(1))/(T - t(2))\} = (UA/MCp)(\text{Heatup Time})$$

where: $t(1)$ = vessel initial temperature; $t(2)$ = final temperature reached during the heatup time; T = constant jacket or coil temperature; M = weight; and Cp = specific heat of the vessel contents (both the weight of the process contents as well as the metal weight of the vessel and their respective Cps must be taken into account).

Similarly, for batch cooling, use the below equation:

$$\ln\{(t(1) - T)/(t(2) - T)\} = (UA/MCp)(\text{Cooldown Time})$$

The above equations can also be used even when the jacket temperature is not constant, provided that the difference in inlet and outlet temperatures is not greater than 10% of the log mean temperature. If so, then one may use the average jacket temperature for T.

For larger changes in jacket temperature, use the below equation for heating:

$$\ln\{(T(1) - t(1))/(T(1) - t(2))\} = (WC/MCp)((k - 1)/k)(\text{Heatup Time})$$

Similarly, for larger changes in jacket temperature, use the below equation for cooling:

$$\ln\{(t(1) - T(1))/(t(2) - T(1))\} = (WC/MCp)((k - 1)/k)(\text{Cooldown Time})$$

where: $T(1)$ = inlet jacket temperature; W = jacket mass flowrate; C = specific heat of jacket fluid and k = e to the exponent UA/WC.

The U-value in all of the above equations is assumed to be constant. If the batch temperature range is large, U will vary and the range must be divided into small increments to get the fraction of the Total Time.

Calculation of Inside (Process-Side) Film Coefficients requires that: 1) Physical property data is accurate, and 2) The vessel/agitator system is geometrically similar to that for which the equation was developed. In almost all cases, some form of the Dittus-Boelter equation (which employs the Nusselt, Reynolds and Prandl Numbers, as well as a Wall Viscosity Correction Factor) is used to calculate the inside film coefficient. In this equation, the exponents of the Reynolds and Prandl Numbers and the viscosity term are empirically determined, along with the System Coefficient (k). The diameter used is the inside diameter of the vessel.

For jacketed vessels, their respective exponents are typically 0.67, 0.33 and 0.14 with (k) varying from as low as 0.33 for retreating blades, up 1.0 for anchor agitators and depending on the Reynolds Number, baffling, type of bottom head, clearances and number of agitator blades. These exponents and k-values are abundant in the literature.

For internal coils, similar Dittus-Boelter equations for Inside (Process-Side) Film Coefficients exist, except that correction terms to take into account ratios of impeller diameter to vessel diameter and coil diameter to vessel diameter are sometimes included. Again, these equations are abundant in the literature.

Fouling Factors, in literature, for use in determining the Overall U-value should be confirmed. Wall Resistances can be significant with thermal conductivities ranging from 0.58 for glass lining up to 218 for copper, both in English units.

The last of the five resistances needed to calculate the Overall U-value are those for the Outside (Heating/ Cooling Fluid Media-Side) Film Coefficients. For jacketed vessels, Outside Film Coefficients also use forms of the Dittus-Boelter equation except that the vessel diameter is replaced by an "equivalent" diameter, which is equal to four times the wetted perimeter of flow in the jacket.

For example, in an annular jacket with spiral baffling (considered as a helical coil), use the liquid media Equivalent Diameter for Heat Transfer, $D(e) = 4p$, where "p" is the pitch of the spiral baffle. Velocities are calculated from the cross-section area, pw, where "w" is the width of the annular space and "w" the effective liquid mass flowrate. Due to extensive leakage, the effective liquid flowrate in the jacket is usually taken as 60% of the actual flowrate to get a conservative film coefficient. Also, the equation should be multiplied by a turbulent-flow correction factor, involving a D(e) and the diameter of the spiral coil.

Many other jacket systems, such as standard annular jackets with no baffles, half-pipe jackets, dimple jackets, as well as internal coils, can also have their Outside (Heating/Cooling Fluid Media-Side) Film Coefficients calculated and be designed, as cited by C.Y. Chen, R. Markovitz, S. Lippa, F. Bondy, et.al., and the Pfaudler Co.

Heat-transfer Area for vessels will preferably employ jackets rather than internal coils because of a lower tendency to foul, easier maintenance and cleaning, cheaper materials of construction, and less problems with circulating catalysts and viscous liquids. Also, jackets usually provide a larger surface area.

Below are some useful points to remember regarding the heat-transfer area for various jackets and coils:

- Dimple Jackets – For a typical jacket with a ½″ dia. dimple weld, in a 2 ½″ square pattern, the ratio of Effective Heat-Transfer Area to Total Heat-Transfer Area = 0.92.

- Standard Annular Jackets (with/without spiral baffling) – Effective Heat-Transfer Area is that wetted by both the vessel's contents and the heat-transfer fluid. To enhance heat transfer, consider agitating nozzles for jacket liquids.

- Half-Pipe Coil Jacket – Standard coils are made from 2″, 3″ and 4″ pipe and are usually composed of an included arc of 120° – 150°. Spacing between coils is typically either ¾″ or 1″, based on the size of the coil. Multiply the area between the half-pipes by 0.60 and add it to the area under the half-pipes to get a conservative Effective Heat-Transfer Area.

- Internal Coils – The Effective Heat-Transfer Area is the total wetted area, based on the coil's outside surface. To obtain this area, it is necessary to know the number of coil turns per foot of coil height.

The last design item deals with pressure drops in jackets and coils. Pressure drops can be significant because a high velocity is required to improve the Overall U, by increasing the jacket or coil film coefficient. For Annular

Jackets with Spiral Baffling, Annular Jackets with No Baffling, Half-Pipe Coil Jackets and Internal Coils, the Fanning equation can be used, each with a different Equivalent Diameter for Fluid Flow, $D'(e)$.

Below are equations for $D'(e)$ for each of the above jackets and coils:

- Annular Jacket with Spiral Baffling: $D'(e) = (2pw)/(p+w)$

- Standard Annular Jacket (without agitation nozzles): $D'(e) = D(jo) – D(ji)$, where $D(jo)$ and $D(ji)$ are the respective outer and inner diameters of the jacket.

- Half-Pipe Coil Jacket: For 120° half-pipe coils, $D'(e) = 0.321d(ci)$, where $d(ci)$ is the inner diameter of the half-pipe coil.

As earlier noted, this has been a brief outline of procedures used for heat transfer design in agitated vessels. For a comprehensive and detailed treatment of this subject, see:

F. Bondy, S. Lippa, "Heat Transfer, Agitated Vessels," Encyclopedia of Chemical Processing and Design," Vol. 25.

Frederick Bondy has over 30 years of successful process engineering experience leading the design of more than 60 refinery, petrochemical, polymer and specialty chemical plants. His experience includes grassroots and revamp projects, as well as pilot plants. Please contact Jerry Lacatena (jlacatena@carmagen.com) if you'd like more information on Carmagen's expertise in this area.

Would you like more information about Carmagen? Please visit our website at **www.carmagen.com**.