DESIGN OF A SMALL HEAT RECOVERY STEAM GENARATOR USING BAYONETS TUBES

Authors

Ferraz, André D.
Lehmkuhl, Willian A.
Azevedo, Jorge G. W.
Machado Jr., Antonio R.
Rocha, Ivan Carlos C. da
Konishi, Ricardo
Sant Anna, Antonio Claudio
Mantelli, Marcia

Abstract

The purpose of this article is study the viability of a small heat recovery steam generator for industries. Conventional waste heat steam generator normaly have high capacities. Low steam generator capacities results on an expensive water or fire tube heat recovery steam generator (HRSG). To develop cheaper equipment for this case the use of finned bayonets tubes can be a solution. Bayonet tubes were use on HRSG in initial of XIX century for military ships. Thorough studyies of sizing bayonets tube were not found in the literature for this application. The design procedure propose here have to be experimentally analyzed before uses. An experimental apparatus is being manufactured in the Heat Pipe Laboratory of Federal University of Santa Catarina, Brazil.

1. Introduction

Energy crisis is an important issue for this century. Among several resources for human life, energy and potable water are two important challenges. Concerning sustainability, reducing energy consumption by using more efficient energy technologies is cheaper and less pollutant than increasing energy offer. Reengineering the energy uses is called Demand Side Management.

The industrial consumption of Natural Gas is an important market share for Natural Gas companies. The commercial experience of these companies in Brazil demonstrates that efficient solutions for Natural Gas use leads to satisfied clients, and consequently to long term supplying contracts.

Increasing energy efficiency in industry involves energy recovering of flue gases and liquid effluents. However, heat recovering has to be interesting from a financial point of view, too.

There are some main points to consider like purchase and installation, investment, amortization, operating cost, tax, insurance and other applications that involve the equipment itself. It is important to know possible ways available and do a technical and economic study to check the operating conditions that reflects advantages.

In an industry, the integration between energy processes using recovering heat systems is one of the best ways to use energy rationally. This also contributes to the environment preservation, reducing fuel consumption and green house gases emissions.

Some industrial processes emit enough hot gases to recover heat. An example of this is the high temperature kilns on metallurgic industries. The energy of these gases can be recovered to generate water steam into appropriate equipment so that recovered energy can be an input energy in other process in the same industry.

Heat Recovery Steam Generator (HRSG) uses hot gases from other process to generate steam. This kind of steam generator is installed before the chimney increasing exhaustion system pressure drop. The way the HRSG is used can bring us an idea for fuel consumption or a better use of it.

Therefore, a replacement of a usual boiler for a HRSG always increases the global efficiency of an industrial plant.

2. Types of steam generators

According to the general classification of boilers, HRSG can be a fire tube or water tube boiler. The selection between fire tube and water tube is determinate by the application. Water tube boilers usually have superior steam generator capacities and work at higher pressures. To make overheat steam is necessary combine an overheating exchange and it's more common on water tube boilers. In industries that have a moderate request for saturate steam, fire tube boilers are more common.

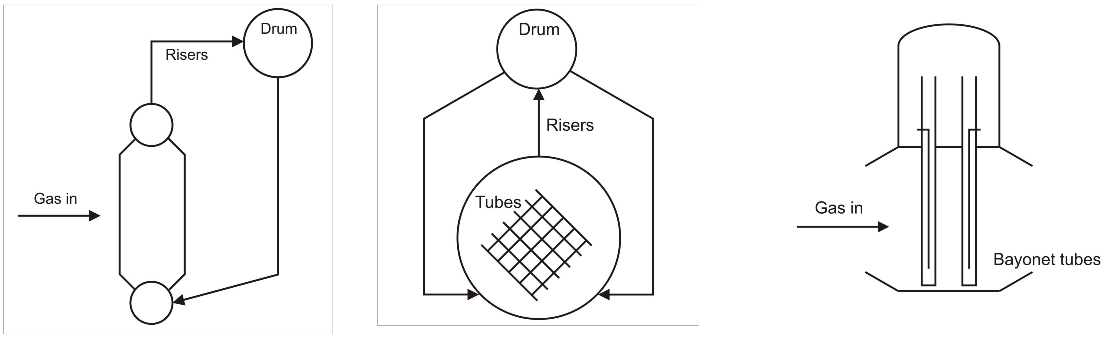
In water tube boilers, water flows into tubes displaced through the way of the hot gases and around the furnace. These tubes are called risers and link an inferior drum to the superior drum. In this way, the water is heating up to shift steam. The risers lead to the upper drum water and steam, the steam is used in the factory and the water returns to the downer drum into no heated tubes called downcomers. The water circulation on water tubes boilers can be forced by pumps or driven by the density difference between the water that flows inside downcomers and the water-steam mixture in the risers.

In fire tube boilers the hot gases flow in submersed tubes and can have an underwater furnace too. This type of HRSG raises the pressure drop on the exhaust system. Radiation heat transfer has a large influence on heating in both of the two construction types described. HRSG can have a supplementary burn to improve its efficiency.

NOMENCLATURE

C_3	correction coefficient for row's number
cp_l	liquid specific heat
D	external diameter
D_i	internal diameter
ρ_l	liquid density
ρ_g	gas density
h	fin high
$h_{ext,\,fin}$	convection heat transfer coefficient for finned tube
h_{boil}	boiling heat transfer coefficient
$h_{\lg}$	heat of vaporization
k	hot gases thermal conductivity
k_l	liquid thermal conductivity
k_{fin}	fin thermal conductivity
k_w	wall thermal conductivity
l	heated length
η	fin efficiency
$\Pr$	hot gases Prandtl number
$\dot{Q}$	heat flux rate
R	thermal resistance
Re	Reynolds number
s	distance between fins
S_{fin}	fin surface area
S_w	surface area between fins
S_{in}	internal surface area
T_{gas}	hot gases temperature
T_s	steam temperature
T_w	wall temperature
w	fin thickness
x_t	transversal distance between tubes
x_l	longitudinal distance between tubes

A small bayonet industrial HRSG is easier to manufacture resulting in cheaper equipment since it has only one pressure vessel. The external flow of gases still permits fin use and keeps the drop pressure low. It's show at Figure 1.



(a) Water tube HRSG (b) Fire tube HRSG (c) Bayonet tube HRSG

Figure 1: HRSG layout.

Nowadays, Bayonet tubes are applied on heaters and condensers; it was first assayed on heat exchanges by Hurd (1946). The flow developing inside bayonet tubes and the link between geometrical parameters was described by Minhas (1995, 1996). Kayansayan (1995) made a design procedure for bayonet boilers and condensers, but in these procedures the phase change occurs on an external surface.

The Figure 2 shows the internal flows proposed for water and steam in bayonet tube. Kakaç (1991) exemplifies a waste heat boiler common on ammonia plants according to the author, but he doesn't show a thorough study of bayonet tube sizing.

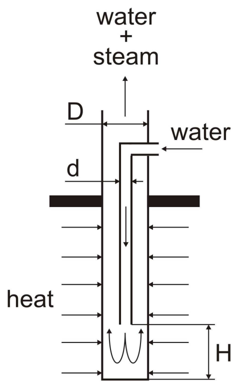


Figure 2: Internal flows and heated surface area.

Like Kakaç, here the HRSG proposes the water boils inside of bayonet tube on annuli zone. So that, bayonet tube HRSG is similar to a water tube steam generator since both phase change occurs inside a tube.

The inner tube does the downcomers work feeding water to the bottom of the outer tube. The water circulation in this equipment is driven by density difference between inner tube liquid and steam on annuli region.

The bayonet tubes for the HRSG proposed have external fins to enlarge the heat transfer surface improving the heat transfer rate with hot gases. Material proprieties, fin's height and thickness and the distance between fins affect the fin efficiency and the heat transfer coefficient according to following equations.

3. Mathematical model

A theoretical model that relates all physical phenomena of heat transfer on bayonet tubes is hard to obtain. Nevertheless, with engineering projects the similarity of thermal and electrical circuits is used. The total thermal resistance of the bayonet tube relates the heat flux rate and temperatures of hot gases and steam according to equation 1.

$$\dot{Q} = \frac{1}{R_{total}} \cdot \left(T_{gas} - T_s\right) \tag{1}$$

The thermal circuit that represents this heat transfer process is show at Figure 3, this circuit does not consider longitudinal losses because of reduced value besides others thermal resistance. So, the value of total thermal resistance is given by the sum of resistances, equation 2.

$$R_{total} = R_{ext} + R_{cond} + R_{boil} \tag{2}$$

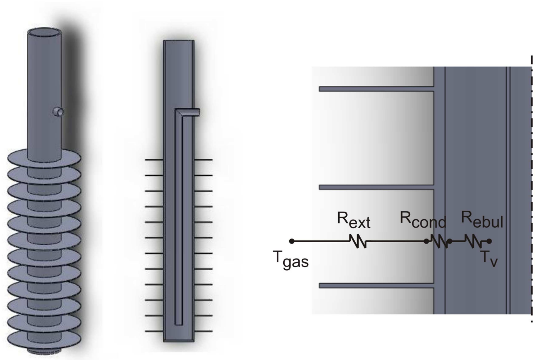


Figure 3: Bayonet thermal circuit.

The resistance R_{ext} refers to external convection on fin tubes, R_{cond} is the conduction resistance through the wall thickness of the tube and R_{boil} is the boiling resistance. Those resistances are calculated by the follows equations:

$$R_{ext} = \frac{1}{h_{ext,fin} \cdot \left(S_{fin} \cdot \eta + S_w\right)} \tag{3}$$

$$R_{cond} = \frac{\ln D/D_i}{2 \cdot \pi \cdot k_w \cdot l} \tag{4}$$

$$R_{boil} = \frac{1}{h_{boil} \cdot S_{in}} \tag{5}$$

The external convective heat transfer coefficient to finned tubes ($h_{ext,fin}$) is given by the equation 6 (ESDU, 1986), and the fin efficiency (η) by equation 7.

$$h_{ext,fin} = \frac{k}{D} \cdot C_3 \cdot 0{,}242 \cdot \mathrm{Re}_{\max}^{0{,}658} \cdot \left(\frac{s}{h}\right)^{0{,}297} \cdot \left(\frac{x_t}{x_l}\right)^{-0{,}091} \cdot \mathrm{Pr}^{1/3} \cdot \left(\frac{\mathrm{Pr}}{\mathrm{Pr}_{\sup}}\right)^{0{,}26} \tag{6}$$

$$\eta = \frac{\tanh\left[h \cdot \sqrt{\frac{2 \cdot h_{ext,fin}}{w \cdot k_{fin}}}\right]}{h \cdot \sqrt{\frac{2 \cdot h_{ext,fin}}{w \cdot k_{fin}}}} \tag{7}$$

The internal heat transfer coefficient in this paper was calculated by Foster and Zubber correlation for nucleate pool boiling although the water-steam mixture flows up in the annuli region, equation 8. If the mixture velocity is low, this approximation doesn’t differ so much. Liu and Winterton's (1991) correlation for flow boiling in tube and annulus is based on a nucleate pool boiling equation, but it wasn't use in this analysis.

$$h_{boil} = 0{,}00122 \cdot \frac{k_l^{0,79} \cdot cp_l^{0,45} \cdot \rho_l^{0,49}}{\sigma^{0,5} \cdot \mu_l^{0,29} \cdot h_{lg}^{0,24} \cdot \rho_g^{0,24}} \cdot (T_w - T_{sat})^{0,24} \cdot \Delta p_{sat}^{\ 0,75} \qquad (8)$$

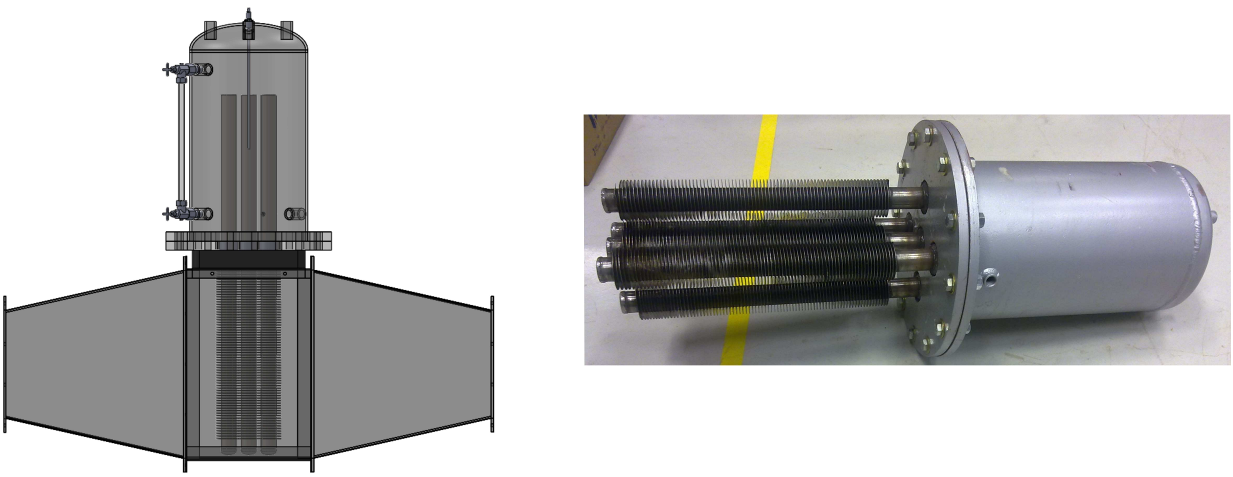
The magnitude of each thermal resistance is show on table 1. There, can be observed that the value of the external convective resistance is superior to the others thermal resistance. So an improvement at the external heat transfer is the easier way to reduce the total thermal resistance, justifying use of fins. Although the magnitude of the boiling resistance was inferior its affects on total thermal resistance is important, and has to be carefully analyzed because boil's correlation can have differences on values.

Table 1: Thermal resistance's magnitude.

Resistance [K/W]	Magnitude
R_{ext}	10^{-3}
R_{cond}	10^{-4}
R_{boil}	10^{-4}
R_{total}	10^{-2}

4. Experimental apparatus

Using Engineering Equation Solver (EES) program this design procedure can be easily made. However its have to be experimentally analyzed before manufactory for industries uses. An experimental apparatus is being manufactured in the Heat Pipe Laboratory of Federal University of Santa Catarina, Brazil. The Figure 4 shows side by side a 3D draw and a picture of the experimental apparatus. It will be installed on a test bench that has a hot gases circulation. With this tests, the design procedures can be calibrate checking the generate capacity of the apparatus and the temperature of the hot gases. This apparatus is a small scale HRSG with five bayonets tubes. With 2200 kg/h of hot gases at 500ºC, this apparatus can generate 68 kg/h of saturate steam according to the design procedure.



(a) (b)

Figure 4: (a) 3D digital model of experimental apparatus; (b) picture of the pressure vessel with bayonet tubes.

5. Results

The proposed designed model was used for sizing a HRSG intended to replace a small steam generator in a high precision casting factory located at south Brazil. This factory needs 150 kg/h of saturated vapor @ 180°C. Nowadays, their expenditure with Natural Gas to generate saturated steam is approximately US$61,000.00 / year. On the other side, they use three sintering kilns, each kilns produces 1320 kg/h of flue gases @ 800 °C. The design tool was used for sizing a HRSG that recovers heat from one of this kiln. As mentioned before, an experimental calibration of the design tool is now needed, but the tool is already useful for evaluate the order the size of the equipment.

Some design parameters was chosen with basis on previous experiences of the authors. The design model calculated the number of bayonets finned tubes of 42 mm external diameter, and fins 14 mm high, 1 mm thick, spaced 6 mm from each other. The design model prescribed a configuration with 13 bayonets tubes. After sizing a pressure vessel where this jacket tubes can fit, a cost assessment for the configuration was performed. The estimated cost for this equipment is US$22,000.00, taking in account the prices of pressure vessel, bayonets tubes, flue gas ducts, operation valves and safety valves. The only disregarded cost in this assessment was the price of a by-pass duct of gases, for the case that the HRSG will not operate

Buying US$22,000.00 equipment for saving US$ 61,000.00 per year is a really interesting investment. Even if there is a 50% difference between theoretical boiling correlation and the experimental correlation to be evaluated, we have yet a very interesting investment.

6. Conclusion

A design model for sizing small heat recovery steam generators made of jacket tubes was developed. This kind of steam generator showed itself cheap equipment, since its geometrical configuration is simpler and easier of manufacture than the two-drums and finned tubes conventional configuration, or the flame inside tubes configuration. This advantage turns the investment in heat recovery steam generation viable in small industries, allowing the increase the global efficiency of using natural gas. For a case studied of a small factory that nowadays consumes 150 kg/h of saturated vapor, the investment pay back time is less than one year. The developed design model showed itself a useful tool for sizing the steam generators. For further work, calibration of the design tool with a experimental model is recommended.

7. References

KAKAÇ, S., Boilers, Evaporators and Condensers, U.S.A., 1991.

MINHAS, H., LOCK, G. S. H. e WU, M., Flow characteristics of an air-filled bayonet tube under laminar conditions, Int. J. Heat Fluid Flow nº. 16, 1995.

MINHAS, H., LOCK, G. S. H, Laminar-turbulent transition in a bayonet tube, Int. J. Heat Fluid Flow nº. 17, 1996.

HURD, N. L., Mean temperature difference in the field of bayonet tube, Indus Engng Chem nº. 38, 1946.

KAYANSAYAN, N., Thermal design method of bayonet tube evaporators and condensers, Int. J Refrig. Vol. 19, nº. 3, 1996.

SMITH. E. M., Advances in thermal design of heat exchangers: a numerical approach: direct-sizing, step-wise ratting, and transients, U.S.A., 2005.

HEWITT, G. F., SHIRES, G. L., BOTT, T. R., Process heat transfer, U.S.A., 1994.

ESDU International plc, High fin staggered tube banks: heat transfer and pressure drop for turbulent single phase gas flow, ESDU item 86022, 1986.

LIU, Z., WINTERTON, R. H. S., A general correlation for saturated and sub-cooled flow boiling in tubes and annuli, bases on a nucleate pool boiling equation, Int. J. Heat Mass Transfer Vol. 34, nº. 11, 1991.
BABCOCK & WILCOX, Steam; its generation and use, U.S.A., 2005.
PERA, H., Geradores de Vapor de Água (Caldeiras), São Paulo, 1966.
BRANAN, C. R., Rules of thumb for chemical engineers, 2002.