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A Python Based Program to Perform Energy Analysis of External Forced Convection Systems

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Abstract

This paper presents AestusLab, a program for studying heat transfer by external forced convection, created with Python 3.5 and PyQt 4.11.4. AestusLab allows the study of heat transfer over ducts with cross flow and over tube banks. The program uses several experimental correlations reported in the literature for solving the problems. There are two different solving methods: cylinders with different cross section and tube banks in different arrangements. In AestusLab-Cylinders, it is possible to perform calculations for circular, square, hexagonal and elliptical sections, depending on the inclination. With AestusLab-Tube Banks, there are two different configurations: in-line and staggered. It was found that the effect of the pipe geometry on the heat loss for different fluids was not significant. The physical properties of the fluid have an important effect on the heat rate, no matter the type of geometry used. A significant effect on the arrangements of tube banks in the outlet temperature of the external fluids was found with a difference in temperature about 2°C between them.

Keywords: Cylinders, tube banks, cross flow, external forced convection

1 Introduction

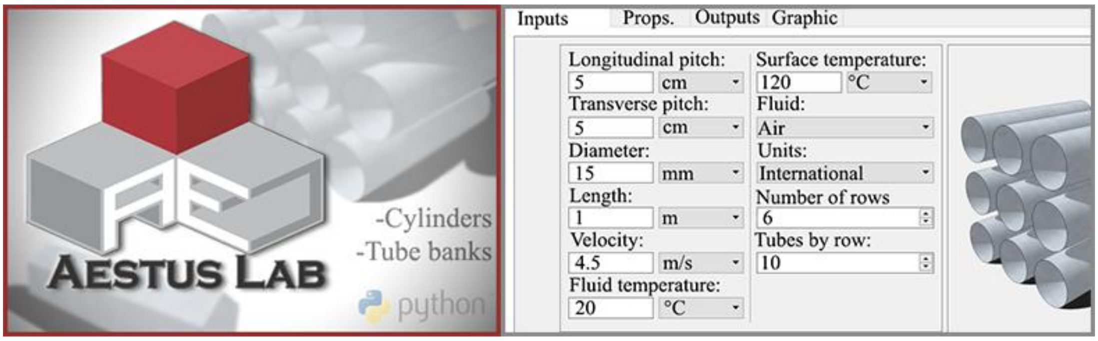
Among the three fields encompassed by transport phenomena, energy exchange is one of the most important due to the energy conservation in the world. Heat transfer is involved in the majority of the processes of energy production, especially convective heat transfer [1]. This type of heat transfer mechanism is important in common situations like in air conditioners, refrigerators, computers, and in heat exchangers of different types like shell-and-tube heat exchangers. Several studies have been done to find methods of heat transfer optimization [2, 3] or to improve the comprehension using numerical analysis [4]. External forced convection involves complex situations that make difficult to obtain analytic solutions forcing the use of experimental correlations [5, 6]. However, due to the technological advances, it is possible to make virtual experimentation using numerical methods to solve the complex equations [2, 4], so it is extremely important for engineers to have an excellent knowledge of convective heat transfer, combining typical theoretical classes with the use of specific software that helps student to go beyond the solution of simple problems. Technological tools represent a big advantage in student learning process since they help to understand quickly and easily energy systems increasing their knowledge and their capacity to give valuable contribution during the design and assessment of heat exchangers [7-9].

In this work, a new program for studying external forced convection, called AestusLab, is presented. The software focus in the assessment of external forced convection over circular and noncircular cylinders, and cross flow over tube banks in two different arrangements, in-line and staggered, using different fluids. It was evaluated the effect of the pipe geometry on the heat loss for different fluids, and the effect of the arrangements of tube banks in the outlet temperature of the external fluids.

2 Methodology

2.1 Presentation of the software

AestusLab is a program created using Python 3.5 and PyQt 4.11.4 which allows the simulation of heat transfer by external forced convection over circular and noncircular cylinders and flow over tube banks, see figure 1. The user can select any fluid from the data base and AestusLab calculates the properties for the temperature of reference. The software is divided into two different categories: AestusLab Cylinders and AestusLab Tube Banks. For each category, there are 4 tabs where the first one the user must introduce the corresponding unit, and AestusLab will make the correct conversion. The second tab shows the properties of the fluid at the temperature of reference. The third tab corresponds to the outputs, which are shown as a table with the unit depending on the system selected. The last tab is for charts, where the user can create different plots and study the variation of all the output versus the inputs.



Longitudinal pitch: 5 cm
Transverse pitch: 5 cm
Diameter: 15 mm
Length: 1 m
Velocity: 4.5 m/s
Fluid temperature: 20 °C
Surface temperature: 120 °C
Fluid: Air
Units: International
Number of rows 6
Tubes by row: 10

Figure 1. Interface software AestusLab Tube Bank

2.2 Fundamental equations used by AestusLab Cylinders.

All equations used in the software follow the nomenclature shown in Table 1.

Table 1. Nomenclature

Variable	**Symbol**	**Variable**	**Symbol**
Diagonal pitch	S_D	Prandtl number	Pr
Diameter	D	Mass flow	$\dot{m}$
Fluid temperature	T_∞	Reynolds number	Re
Heat rate	Q	Superficial Area	A_s
Heat transfer coefficient	h	Surface Temperature	T_s
Longitudinal pitch	S_L	Thermal conductivity	k
Maximum velocity	V_{max}	Transverse pitch	S_T
Nusselt number	Nu	Velocity	V
Inlet temperature	Ti	Exit temperature	Te

For cylinders with different geometries, it was necessary to calculate the convective heat transfer coefficient, to assess the heat transfer rate. The Nusselt number with some empirical correlations were used, based on the corresponding geometry, the Reynolds number, and Prandtl number. The general equation used for different geometries was:

$$Nu_{cyl} = \frac{hD}{k} = CRe^{m}Pr^{1/3} \qquad (1)$$

where values for C and m range from (0.027 to 0.989) and (0.330 to 0.805) respectively, depending on the geometry of the cross section.

2.3 Fundamental equation used by AestusLab Tube Banks:

The arrangement of the tube banks is characterized by the transverse pitch, longitudinal pitch and diagonal pitch between tube centers [6]. The tubes in the bank can be arranged in two ways, in-line or staggered. The diagonal pitch can be calculated from the transverse and longitudinal pitch as follows:

$$S_D = \sqrt{S_L^2 + (S_T/2)^2} \tag{2}$$

For calculating the Reynolds, the maximum velocity inside the bank must be used, and it can be calculated depending on the geometry. For in-line arrangement, the maximum velocity is:

$$V_{max} = \frac{S_T}{S_T - D}\, V \tag{3}$$

For staggered arrangement, when $S_D < (S_T + D)/2$, the maximum velocity:

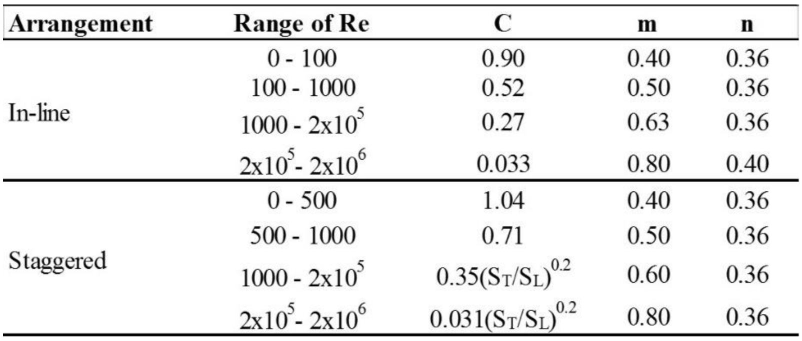
$$V_{max} = \frac{S_T}{2(S_D - D)}\, V \tag{4}$$

For $S_D \geq (S_T + D)/2$, equation 3 is used. The Nusselt number is calculated using equation 5.

$$Nu = CRe^m Pr^n (Pr/Pr_s)^{0.25} \tag{5}$$

The parameters *C*, *m*, and *n* are shown in table 2

Table 2. Parameter equation Zukauskas tube banks



Arrangement	Range of Re	C	m	n
In-line	0 - 100	0.90	0.40	0.36
	100 - 1000	0.52	0.50	0.36
	1000 - $2x10^5$	0.27	0.63	0.36
	$2x10^5$ - $2x10^6$	0.033	0.80	0.40
Staggered	0 - 500	1.04	0.40	0.36
	500 - 1000	0.71	0.50	0.36
	1000 - $2x10^5$	$0.35(S_T/S_L)^{0.2}$	0.60	0.36
	$2x10^5$ - $2x10^6$	$0.031(S_T/S_L)^{0.2}$	0.80	0.36

Once the Nusselt number is calculated, the heat transfer coefficient *h* can be calculated from the definition of Nusselt, and then it is possible to obtain the heat rate *Q* from Newton's cooling law:

$$Q = hA_s\Delta T_m \tag{6}$$

Where ΔT_m, is the log mean temperature. The mass flow is calculated using the equation 7:

$$\dot{m} = \rho_i V (N_T S_T L) \tag{7}$$

The exit temperature is calculated as follow:

$$T_e = T_s - (T_s - T_i) \exp\left(-\frac{A_s h}{\dot{m} Cp}\right) \tag{8}$$

3 Results and discussion

This section shows the results obtained from two case studies using AestusLab, subsequently, they are compared with results reported in the literature [6].

3.1 Heat loss of a steam pipe in two fluids, air and Carbon Dioxide

In this case, the heat loss from a steam pipe was calculated. The diameter of the long tube is 10 cm, the external temperature is 110 °C. The pipe is exposed to the fluid. The velocity of the fluid (air and carbon dioxide) is 8 m/s and its temperature is 10 °C. The results per units of length in meter, obtained using AestusLab and the reported in the literature are shown in table 3. The error was calculated.

Table 3. Results obtained for air with AestusLab compared with literature

Parameter	**Result by AestusLab**	**Result by literature**	**Error (%)**
Re	4.211×10^4	4.219×10^4	0.19
Nu	124.3	124	0.24
Pr	0.7202	0.7202	0.00
h (W/m^2°C)	34.9	34.8	0.29
Heat rate (W)	1096	1093	0.27

The effect of the fluid velocity in the heat transfer rate was studied for two different gases, see figure 2. It can be seen that an increase in the velocity causes an increase in the heat transfer rate with a higher effect in circular pipes than in square and hexagonal pipes. The smooth surface of the circular pipes let a better contact of the fluid with the pipe surface increasing the heat transfer rate. On the other hand, it can be seen the effect of the physical properties of the fluid on the heat rate having a higher efficiency when using CO_2, no matter which geometry is being used. This effect is small at low velocity and increases proportionally to the velocity.

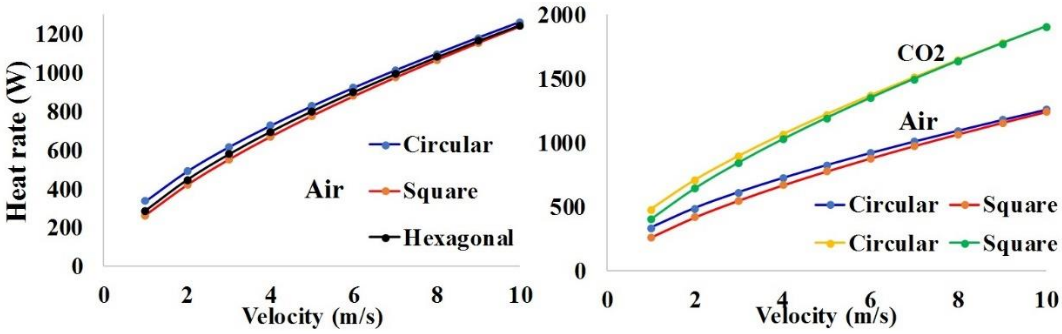


Figure 2. Heat rate as a function of velocity, duct geometry, and type of fluid

3.2 Preheating Air, Carbon Dioxide and methane by Geothermal Water inside a Tube Bank

Air, CO_2, and CH_4 are preheated with geothermal water at 120°C flowing inside a tube bank located in a duct. The external fluids (air, CO_2, and CH_4) are at 20°C with a mean velocity of 4.5 m/s. The outer diameter of the tubes is 1.5 cm and they are arranged in-line with longitudinal and transverse pitches of 5 cm. There are 6 rows in the flow direction with 10 tubes in each row. The results obtained with AestusLab and the reported in the literature [6] are compared in table 4.

Table 4. Results obtained with AestusLab compared with AestusLab

Parameter	**Result by AestusLab**	**Result by literature**	**Error (%)**
Outlet temper. (°C)	29.42	29.41	0.034
Re	6190	6189.2	0.013
Nu	56.19	56.19	0.000
h (W/m^2°C)	95.49	95.45	0.042
Mass flow (kg/s)	2.709	2.709	0.000
Heat rate (W)	2.571x10^4	2.570x10^4	0.039

As can be seen in figure 3, if the fluid velocity increases, the outlet temperature decreases. If the velocity of the fluid is high, it takes a short time for leaving the tube bank, meaning that the residence time decreases. Short time inside the bank results in a short time for energy transfer, causing a lower outlet temperature in the external fluid. The effect is higher for CO_2 than for air and CH_4 due to the difference in their physical properties since the surface bank tube temperature remains constant, it results in an increase of the heat loss when increasing the velocity. The configuration of the bank tube has an important effect as well, with a difference in temperature about 2°C between them, see figure 3c and 3d. This plot helps to decide what kind of configuration to use depending on what is desired, heating or cooling and it helps to decide what kind of fluid to use.

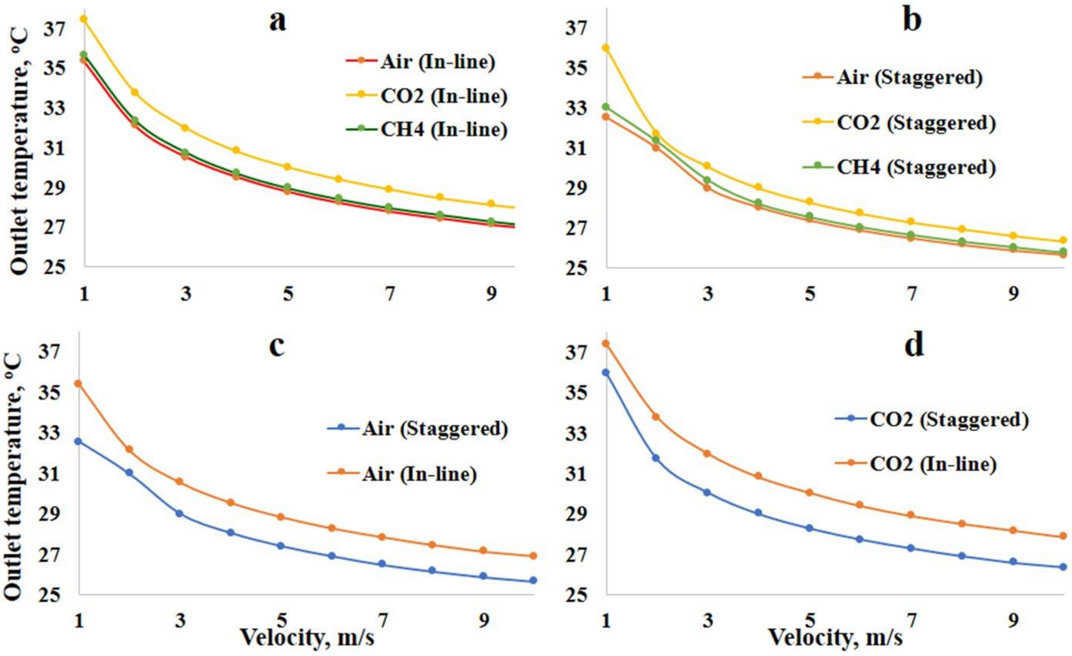


Figure 3. Outlet gas temperature as a function of velocity, a) and b) effect of the fluid on different arrangement of the bank tubes, c) and d) effect of the arrangement of the bank tubes on different fluids

4 Conclusion

A software for studying heat transfer by external forced convection named AestusLab was presented for two different heat transfer systems. It let to simulate heat transfer over cylinders and tube banks in two configurations with a library of different fluids for the external and internal fluids. AestusLab-Cylinders make simulations where the velocity of the fluid, diameter of tube, temperature of fluid and kind of geometry are required, and it calculates the Reynolds and Nusselt number, heat transfer coefficient, and the heat rate. In order to achieve this, the program uses a collection of experimental correlations found in the literature. AestusLab-Tube Bank makes calculations for inputs such as tube bank arrangement, diameter of tubes, temperature of fluid and pipe surface, fluid velocity, longitudinal and transverse pitch, number of rows and columns to determine the outlet temperature, Reynolds and Nusselt number, heat transfer coefficient, mass flow and heat transfer. The effect of the fluid velocity in the heat rate was studied for two different gases where it was found that an increase in the velocity causes an increase in the heat rate with a higher effect in circular pipes than in square and hexagonal pipes due to the smooth surface of the duct. The physical properties of the fluid have an important effect on the heat rate, no matter the type of geometry used. This effect is small at low velocity and increases proportionally to the velocity. In the tube bank, when the fluid velocity increases, the outlet temperature decreases due to the decreasing in residence time. The effect is higher for CO_2 than for air and CH_4 due to the difference in their physical properties. The configuration of the bank tube has an important effect as well, with a difference in temperature about 2^{o}C between them.

References

[1] D. Liu, Y. L. Zheng, A. Moore and M. Ferdows, Spectral element simulations of three-dimensional convective heat transfer, *Int. Journal of Heat and Mass Transfer*, **111** (2017), 1023-1038.
https://doi.org/10.1016/j.ijheatmasstransfer.2017.04.066

[2] E. Umar, K. Kamajaya and N. Tandian, Experimental Study of Natural Convective Heat Transfer of Water-ZrO_2 Nanofluids in Vertical Sub Channe, *Contemporary Engineering Sciences*, **8** (2015), no. 35, 1593-1605.
https://doi.org/10.12988/ces.2015.511302

[3] I. F. Meza, L. G. Obregon and A. Herrera, L. Quiñones, Experimental Determination of New Statistical Correlations for the Calculation of the Heat Transfer Coefficient by Convection for Flat Plates, Cylinders and Tube Banks, *INGE CUC*, **13** (2017), no. 2, 9-17.
https://doi.org/10.17981/ingecuc.13.2.2017.01

[4] O. Otieno and A. Manyonge, J. Bitok, Numerical Computation of Steady Buoyancy Driven MHD Heat and Mass Transfer Past an Inclined Infinite Flat Plate with Sinusoidal Surface Boundary Conditions, *Applied Mathematical Sciences*, **11** (2017), no. 15, 711-729. https://doi.org/10.12988/ams.2017.7127

[5] D. Kern, *Procesos de Transferencia de Calor*, CECSA, 1999.

[6] Y. Cengel, *Heat and Mass Transfer: Fundamentals and Application*, 5 ed., McGraw-Hill, 2015.

[7] R. Gourde, B. Akih-kumgeh, A Matlab program for the determination of thermodynamic properties of steam, *International Journal of Mechanical Engineering Education*, **45** (2017), no. 3, 228-244.
https://doi.org/10.1177/0306419016682146

[8] L. G. Obregon, L. F. Arrieta, G. E. Valencia Ochoa, Thermal Design and Rating of a Shell and Tube Heat Exchanger Using a Matlab GUI, *Indian J. Sci. Technology*, **10** (2017), no. 25, 1-9.
https://doi.org/10.17485/ijst/2017/v10i25/114038

[9] L. G. Obregon, L. F. Arrieta y G. E.Valencia, A Matlab Program for the Design and Simulation of Cooling Towers, *Chem. Eng. Trans.*, **57** (2017), 1585-1590.

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