IOP Conference Series: Materials Science and Engineering

PAPER • OPEN ACCESS

Parametric Sensitivity Analysis of Automobile Radiator Performance

To cite this article: Mohamed H.S. Bargal *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **563** 042038

IOP Conf. Series: Materials Science and Engineering **563** (2019) 042038 doi:10.1088/1757-899X/563/4/042038

Parametric Sensitivity Analysis of Automobile Radiator Performance

Mohamed H.S. Bargal[1,2], Mohamed A. A. Abdelkareem[1,3], Yiping Wang [1,a]

[1]School of Automotive Engineering, Wuhan University of Technology, Wuhan, 430070, China.

[2]Department of Mechanical Power Engineering and Energy, Faculty of Engineering, Minia University, El-Minia 61517, Egypt.

[3]Automotive and Tractors Engineering Department, Faculty of Engineering, Minia University, El-Minia, 61111, Egypt.

[a] Corresponding author: m.bargal@mu.edu.eg, wangyiping@whut.edu.cn

Abstract: The automotive radiator is an important part for automotive engines regarding its direct influence on the thermal performance of the engine. This paper presents a theoretical parametrical sensitivity analysis of an automotive radiator based on the effectiveness-NTU method. In this manner, the paper firstly focuses on the influence of operating conditions of both the water and air including inlet temperatures and Reynolds numbers on the radiator effectiveness, heat transfer rate, and the pressure drop. Furthermore, the sensitivity of the radiator responses versus these operating conditions is provided. Given the obtained results, it is concludingly reported that the radiator effectiveness correlates significantly to the water Reynolds number and the water inlet temperature rather than its correlation to the air Reynolds number and air inlet temperature. While the heat transfer rate correlates strongly to the inlet temperatures of the water and air, respectively, while the heat transfer rate weakly responded to the Reynolds numbers of the water and air. On the third hand, the water pressure drop presented higher sensitivity change at lower water temperatures.

1. Introduction

There are many heat exchanger types that are used in various fields for decades such as in the automotive, refrigeration, air conditioning, and chemical industries. In the automotive industry, the compact heat exchanger type is mainly used to remove the excess heat from the engine to maintain engine desirable operating temperature. This type is also called the radiator which has a large heat transfer area per unit volume [1], and thereby it can provide higher heat transfer rates for light vehicles which are preferred due to the direct relationship between fuel consumption and automotive weight. Thus, the radiator has a vital role in improving engine performance.

In the literature, most of the papers have focused on improving the performance of automotive radiators either by the operating factors for both coolant and air [2-5] or by the radiator's geometry and design factors [3, 6-8]. The geometry and design factors include the size, shape, and material for tubes and fins. While the operating factors include changing the mass flow rates, Reynolds numbers, and inlet temperatures for the water and air. The sensitivity of the radiator performance against the operational parameters has not been addressed in the literature.

The present work aims to present a detailed parametrical sensitivity analysis of the radiator's operational conditions versus the radiator performances. Firstly, the parametrical analysis included the working conditions of both fluids (Reynolds numbers and inlet temperatures) on the effectiveness of the radiator and the amount of heat dissipation from a car radiator as well as the water pressure drop. Thereafter, a sensitivity analysis of the radiator effectiveness, heat transfer rate and pressure drop versus the aforementioned parameters is presented.

2. Data description

In this section, the radiator model and the necessary input data are given based on the literature regarding comprehensive parametrical sensitivity simulations. The characteristics of the radiator considered in this study are obtained from [9]. The radiator is a cross-flow heat exchanger with unmixed air and water as coolants which is considered an automobile radiator. This radiator consists of 34 flat tubes and around 305 mini-channels per column that represent the fins between the radiator tubes. These serpentine fins and the tubes are made from aluminum which has a thermal conductivity of 238 W/m k. The water flows upward through the vertical tubes with a rectangle-shaped cross-section in which the flat tubes are used to enhance the heat transfer from the radiator and at the same time minimize the flow resistance. This is due to the lower drag profile of the flat tubes compared to the round tubes what make the flat tubes thereby are more popular in automotive radiator applications [1, 10]. The core dimensions terms of the length, height, and width are 394*330*22 mm, respectively. The geometrical characteristics of the radiator's tubes and fins are summarized in Table 1, while the range of the operating variables is listed in Table 2.

Table 1. Geometry description of a radiator [9].

Description	Parameter	Value
Tube	Length (m)	0.022
	Height (m)	0.33
	Width (m)	0.002
	Thickness (m)	0.00008
	Hydraulic Diameter (m)	0.0034
	Area (m^2)	0.500
Fin	Length (m)	0.022
	Height (m)	0.001
	Width (m)	0.01
	Thickness (m)	0.00008
	Hydraulic Diameter (m)	0.0018
	Area (m^2)	4.864

Table 2. The range of operating conditions for air and water.

Condition	Range		
	-45%	Normal	+45%
Air Temperature, ^{o}c	11	20	29
Water Inlet Temperature, ^{o}c	35.75	65	94.25
Air Reynolds Numbers	825	1500	2175
Water Reynolds Numbers	412.5	750	1087.5

3. Mathematical Model

In this section, the corresponding mathematical modelling of the radiator is presented based on [3, 11-15]. The inputs parameters include the inlet temperatures, Reynolds numbers, core dimensions, tubes, and fins besides other details like the properties of flows (density, specific heat capacity, Prandtl number, thermal conductivities, and viscosity) and a number of fins and tubes etc. Therefore, the thermal performances of the radiator can be calculated by some theoretical formulas. The calculations were done on both the air and the water for calculating the heat transfer rate.

3.1. Air side calculation

Initially, the airside calculations include the air convection heat transfer coefficient and the fin performance besides the air heat capacity rate. Since the airflow is laminar flow in this analytical study, the Nusselt number is calculated as shown in Eq. (2), in accordance with [14]. The air and water properties are evaluated at the arithmetic mean of the inlet and outlet temperatures of the radiator fluids.

$$\mathrm{Re_a} = \left(\frac{\mathrm{u\rho Dh}}{\mu}\right)_{\mathrm{air}} \quad (1)$$

$$\mathrm{Nu_a} = [10.145 * \ln(\mathrm{Re_a} - 46.081)]\mathrm{Pr_a}^{0.33} \quad (2)$$

$$\mathrm{h_a} = \left(\frac{\mathrm{Nu\,k}}{\mathrm{Dh}}\right)_{\mathrm{air}} \quad (3)$$

$$\mathrm{C_a} = \dot{\mathrm{m}}_\mathrm{a}\,\mathrm{C_{P,a}} \quad (4)$$

Where u, ρ, ṁ and μ are the velocity, density, mass flow rate, and the dynamic viscosity. Pr, k, C_p, and Dh are the Prandtl number, thermal conductivity, specific heat capacity at constant pressure and the hydraulic diameter, respectively. While Re, Nu, h, and C are the Reynolds number, Nusselt number, convection heat transfer coefficient, and the heat capacity rate, respectively, for both air and water.

The fin efficiency and effectiveness are related to the performance of the fin with different quantities. However, they are related to each other as seen in Eqs. (5 and 6).

$$\eta_f = \frac{\tanh ml}{ml} \quad (5)$$

where

$$m = \sqrt{\frac{2\mathrm{h_a}}{\mathrm{k_f}\delta_\mathrm{f}}}$$

$$\eta_0 = 1 - (1 - \eta_f)\left(\frac{A_f}{A_0}\right) \quad (6)$$

Where η_f, η_0, m and l are the total surface temperature effectiveness, fin efficiency of plat fin, fin length from primary to the midpoint between tubes and fin parameter, respectively. While A_0 is the total surface area of airside and A_f is the fin area.

3.2. Water side calculation

In this section, the convective heat transfer coefficient and water heat capacity are calculated similarly to the air side calculations. Furthermore, the water pressure drop which occurs in the radiator's tubes is calculated based on Eqs. (11 and 12). Since the water Reynolds numbers are less than 2100, the water Nusselt numbers could be calculated as fully developed laminar flow through the pipes at constant wall temperature, in accordance with [12].

$$\mathrm{Re_w} = \left(\frac{\mathrm{u\rho Dh}}{\mu}\right)_{\mathrm{water}} \quad (7)$$

$$\mathrm{Nu_a} = 0.951\,\mathrm{Re_w}^{0.173}\mathrm{Pr_a}^{0.3} \quad (8)$$

$$\mathrm{h_w} = \left(\frac{\mathrm{Nu\,k}}{\mathrm{Dh}}\right)_{\mathrm{water}} \quad (9)$$

$$\mathrm{C_w} = \dot{\mathrm{m}}_\mathrm{w}\,\mathrm{C_{P,w}} \quad (10)$$

The water pressure drop is a key factor to evaluate the used pump power for water in which it is calculated from the following equations [13].

$$\Delta\mathrm{P} = \frac{\rho_\mathrm{w}\,\mathrm{u_w^2}}{2}\,f\,\frac{4H}{\mathrm{Dh_w}} \quad (11)$$

$$f * Re_w = 24[1 - 1.3553\alpha^* + 1.9467\alpha^{*2} - 1.7012\alpha^{*3} + 0.9564\alpha^{*4} - 0.2537\alpha^{*5}] \quad (12)$$

Where ΔP, f, α^*, and H are the water pressure drop, the fraction factor, the short side of a rectangular cross-section and the total water flow length, respectively.

3.3. Heat transfer rate calculations

Based on the aforementioned equations, the overall heat transfer coefficient (U), the number of heat transfer units (NTU) and the Heat capacity rate ratio (C_r) are calculated to get the heat exchanger effectiveness (ε) and then the actual heat transfer rate of the radiator. In Eq. (13), the fouling factors are neglected.

$$\frac{1}{UA} = \frac{1}{\eta_o A_o h_a} + \frac{\delta_t}{k_t A_t} + \frac{1}{h_w A_i} \quad (13)$$

Where A is the heat transfer surface area, k is thermal conductivity, δ is the thickness. Whereas the subscripts o, a, t, f, w and i denote for the airside, air, tube wall, fin water, and the waterside, respectively.

$$NTU = \frac{UA}{min(C_a, C_w)} \quad (14)$$

$$C_r = \frac{min(C_a, C_w)}{max(C_a, C_w)} \quad (15)$$

$$\varepsilon = 1 - exp\left\{\frac{NTU^{0.22}}{C_r}[exp(-C_r NTU^{0.78}) - 1]\right\} \quad (16)$$

Where, this equation represents the cross-flow unmixed fluid in which the radiator effectiveness is 30-59 %.

$$Q = \varepsilon\, min(C_a, C_w)\,(T_w - T_a)_{inlet} \quad (17)$$

Where Q is the actual heat transfer rate while T_w and T_a are the inlet temperatures of the water and air.

4. Results and Discussions

4.1. Parametric Analysis

The influence of radiator operating conditions including both fluids parameters on radiator effectiveness, the amount of heat dissipation and water pressure drop is addressed.

4.1.1. Radiator effectiveness

The heat exchanger effectiveness enables determining the heat transfer rate without knowing the outlet temperatures of the fluids. On the contrary, the log mean temperature difference (LMTD) method which requires the outlet temperatures of the fluids. Therefore, the ε-NTU method is considered for calculating the radiator effectiveness in a simplified way. The ε-NTU can determine the heat transfer performance of a specified car radiator [16]. What stands out in Figure 1 is that the radiator effectiveness has risen with the increase of all working conditions except the water Reynold number that presented a counter-wise trend. In Figure 1a, at constant water inlet temperatures, the enhancing of the radiator effectiveness was smaller when the air temperature increased which is under 5% owing to the weak correlation of the air heat capacity and thereby the capacity rate. On the contrary, for a constant air temperature, the radiator effectiveness enhanced by 57% against the water inlet temperature variation because of the increase of the number of heat transfer units (NTU) and the drop in the heat capacity rate. Obviously, the radiator effectiveness dropped at higher water Reynolds numbers as shown in Figure 1b due to the increase in the water flow rate and velocity. Although, the overall heat transfer is improved the NTU still strongly decreased owing to the growing up of the water heat capacity. There is no obvious effect of the air Reynolds numbers on the radiator effectiveness because of its small value that is completely unlike the water Reynolds numbers impact.

4.1.2. Radiator heat transfer rate

The main role of the radiator is to remove the heat from the engine to prevent engine overheating that decreases its performance. Whenever a car radiator can remove more heat to ambient air with the best form, whenever the thermal performance of the engine is improved. The heat removal process directly depends on the temperatures difference between the inlet and exit for both the hot flow and cold flow. More precisely, it changes with the change of the inlet temperatures difference between the water and air beside the effectiveness and the minim capacity rate according to Eq. (17). Figure 2 illustrates the dissipated heat from a car radiator with respect to different operational factors. In terms of temperatures parameters (Figure 2a), there is an obvious effect of the temperatures for both fluids on the heat transfer rate. Following the increment of the water inlet temperature and the decrease of the air temperature, a considerable increase in the dissipated heat is observed hitting a maximum value of 18 kW for recording water and air temperatures of 94.25 and 11 °C, respectively. Obviously, the heat transfer rate has grown whenever the water and air Reynolds numbers increased as shown in Figure 2b due to the increase in the convective heat transfer coefficients for both air and water.

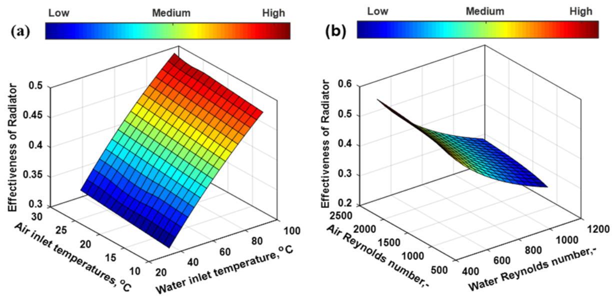

Figure 1. Radiator effectiveness versus operating parameters.

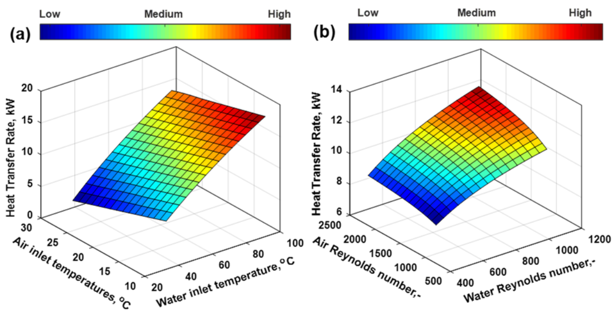

Figure 2. Heat transfer rate versus the operating parameters.

4.1.3. Water pressure drop

The influence of the operational factors on the water pressure drop is illustrated in Figure 3. It is axiomatic that the pressure drop for any fluid mainly depends on the fluid properties. Therefore, the air operation conditions have a weak influence on the water pressure drop which is obvious in Figure 3a and b. Whereas, the water pressure drop decreased significantly when the water temperatures increased as shown in Figure 3a because of the decrease of both liquid density and dynamic viscosity due to the interstitial fluid molecules. On the other hand, in Figure 3b, the pressure drop increased for higher water Reynolds numbers to reach 3 kPa owing to an increase in the flow velocity levels inside radiator tubes.

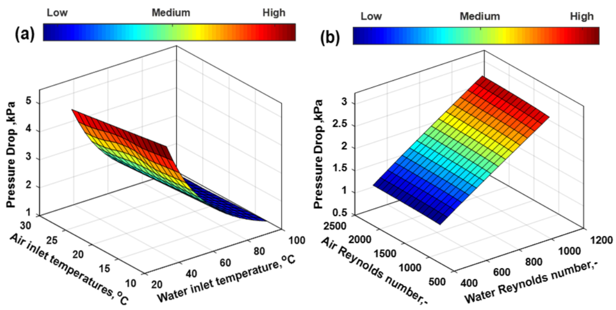

Figure 3. Water pressure drop versus the operating parameters.

4.2. Sensitivity against the operating parameters

In this section, the results present the sensitivity change in radiator effectiveness, heat transfer rate and water pressure drop of an automotive car radiator with respect to operation conditions including Reynolds number and inlet temperature for both fluids to assess of thermal performance for the car radiator.

4.2.1. Radiator effectiveness sensitivity

According to Eq. (16), the heat exchanger effectiveness is a function of the number of transfer units and the capacity ratio. The radiator effectiveness is directly proportional to the NTU and reversely with the capacity ratio. In Figure 4, the sensitivity analysis result of the vehicular radiator effectiveness is revealed versus the variation of the water and air operational conditions. With increasing of all working parameters values, the effectiveness of the car radiator is enhanced except the water Reynold number that presented a counter-wise trend as in Figure 4. The radiator effectiveness has improved with 19%, 3% and 2% versus the inlet water temperature, the air Reynolds number, and the inlet air temperature, respectively, for a 45% increase in the normal values of the aforementioned parameters. In contrast, the radiator effectiveness increased by 40% for a 45% decrease in the water Reynolds number while it decreased by 21% for a 45% increase in the water Reynolds number. Concludingly, the increase in the water Reynolds number has a significant negative impact on the radiator effectiveness because of the water heat capacity increment and therefore the increase of the heat capacity rate. This is also in addition to the NTU reduction that causes a drop in the radiator effectiveness.

4.2.2. Heat transfer rate sensitivity

Figure 5 indicates the heat transfer rate sensitivity against the operation parameters of car radiator at ±45% variation referenced from the parameters normal values. Obviously, the heat transfer rate has grown by nearly 35% and 12% whenever the water and air Reynolds number increased, respectively. Although the radiator effectiveness strongly decreased at higher water Reynolds numbers, the heat transfer rate conversely raised because of the water heat capacity which strongly increased by 141% and thereby recompensed the drop-in radiator effectiveness value. On the contrary, when the air Reynolds number has grown up, the radiator effectiveness has also raised owing to the drop in the capacity rate that is because of a high increase in the air heat capacity. With regards to the inlet water temperature, the increase of the water temperature inlet to a radiator from 35.75 to 94.25 °C leads to a significant increase in the heat transfer rate from 4.35 to 16.12 kW, by nearly 271%. There are two reasons for this significant increase in heat transfer rate according to Eq. (17). Firstly, the increasing of the inlet temperature difference between water and air and secondly the increase of the radiator effectiveness reaching 0.5. As a result, the heat transfer rate has significantly grown up although the heat capacity of water decreased. In the same sense, the heat transfer rate risen by 21% for a -45% decrease in the inlet air temperature while it has dropped by 21% when the inlet air temperature increased by 45% of its normal value. Finally, it is inferred that the radiators should be operated with the best performance which is available within the cold regions and the engine at the maximum load. Concludingly, the radiator ability to remove the greatest amount of heat outside the engine could be obtained at lower ambient air temperature and maximum inlet water temperature.

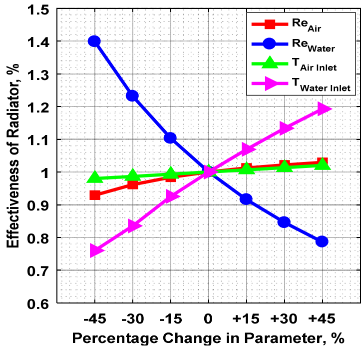

Figure 4. Radiator effectiveness sensitivity.

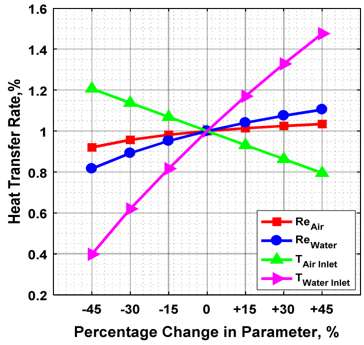

Figure 5. Heat transfer rate sensitivity.

4.2.3. Water pressure drop sensitivity

The air operation conditions have a weak influence on the water pressure-drop which is obvious in Figure 6. But the heat transfer rate increased by 12% at the expense of a slightly increasing for pressure drop by nearly 3% for a changed air Reynolds number from 825 to 2175. Noteworthy, when the variation of the ambient air temperatures with 45%, the dissipated heat from a radiator dropped from 13.2 to 8.7 kW whilst the water pressure-drop slightly reduced. As a result, higher air temperatures are not preferred because of its effect on the car radiator performance although increasing of air velocities. the water pressure-drop remarkedly reduced at the high-water temperatures as revealed in Figure 6. The maximum pressure drop was 4854 Pa at the lowest water inlet temperature (37.75 ^{o}C). In this manner, the high temperature of the hot water entering the radiator increases the heat dissipation at low consumption rates for water pumping power due to lack of water pressure drop. What has been also observed in Figure 6 is that the pressure-drop presented higher sensitivity change at lower water temperatures while a lower sensitivity was shown for the Reynolds numbers of air (do not exceed 2%). As mentioned above, the higher water Reynolds numbers lead to higher heat dissipation but also increase the water pressure drop by nearly 121%. However, it is recommended to increases the water Reynolds numbers to increase the radiator heat dissipation by 35%. With the awareness that the water flow still was a laminar flow in this study.

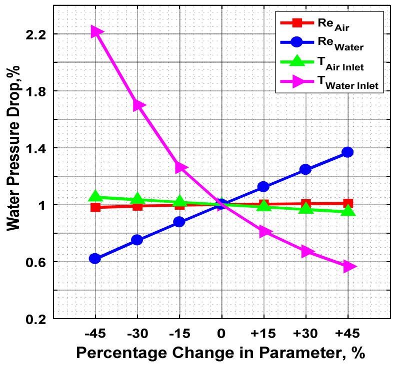

Figure 6. Water pressure drop sensitivity.

5. Conclusion

This paper presented a set of theoretical parametric and sensitivity analyses on the automotive radiator based on the ε-NTU method. The main conclusions are as follows:

1.The radiator effectiveness enhanced with increasing of all working condition values except the water Reynold number that presented a counter-wise trend strongly.

2.The heat transfer rate correlates strongly to the inlet temperatures of the water and air, respectively, while the heat transfer rate weakly responded to the Reynolds numbers of the water and air.

3.The water pressure drop presented higher sensitivity change at lower water temperatures while on the other hand lower sensitivity was shown at all the air operation conditions.

Acknowledgment

The research was supported by State's Key Project of Research and Development Plan (Grant No. 2018YFB0105301). M.H.S. Bargal gratefully acknowledges the Chinese Scholarship Council (CSC) for financial support for his MSc study.

References

[1] Leong K, Saidur R, Kazi S, Mamun A. Performance investigation of an automotive car radiator operated with nanofluid-based coolants (nanofluid as a coolant in a radiator). Applied Thermal Engineering. **30** (2010).

[2] Gollin M, McAssey EV, Stinson C. Comparative performance of ethylene glycol/water and propylene glycol/water coolants in the convective and forced flow boiling regimes. SAE Technical Paper; 1995.

[3] Charyulu DG, Singh G, Sharma J. Performance evaluation of a radiator in a diesel engine—a case study. Applied Thermal Engineering. **19** (1999).

[4] Lin C, Saunders J, Watkins S. The effect of changes in ambient and coolant radiator inlet temperatures and coolant flowrate on specific dissipation. SAE Technical Paper; 2000.

[5] Chen J, Wang D, Zheng L. Experimental study of operating performance of a tube-and-fin radiator for vehicles. Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering. **215** (2001).

[6] Witry A, Al-Hajeri M, Bondok AA. Thermal performance of automotive aluminium plate radiator. Applied thermal engineering. **25** (2005).

[7] Oliet C, Oliva A, Castro J, Pérez-Segarra C. Parametric studies on automotive radiators. Applied thermal engineering. **27** (2007).

[8] Sainath K, Akella S, Reddy TKK. Experimental and computational analysis of radiator and evaporator. Materials Today: Proceedings. **2** (2015).

[9] Peyghambarzadeh S, Hashemabadi S, Naraki M, Vermahmoudi Y. Experimental study of overall heat transfer coefficient in the application of dilute nanofluids in the car radiator. Applied Thermal Engineering. **52** (2013).

IOP Conf. Series: Materials Science and Engineering **563** (2019) 042038 doi:10.1088/1757-899X/563/4/042038

[10] Vasu V, Rama Krishna K, Kumar A. Thermal design analysis of compact heat exchanger using nanofluids. International Journal of Nanomanufacturing. **2** (2008).
[11] Kays WM, London AL. Compact heat exchangers. (1984).
[12] Maiga SEB, Palm SJ, Nguyen CT, Roy G, Galanis N. Heat transfer enhancement by using nanofluids in forced convection flows. International journal of heat and fluid flow. **26** (2005).
[13] Shah RK, Sekulic DP. Fundamentals of heat exchanger design: John Wiley & Sons; 2003.
[14] Vithayasai S, Kiatsiriroat T, Nuntaphan A. Effect of electric field on heat transfer performance of automobile radiator at low frontal air velocity. Applied thermal engineering. **26** (2006).
[15] Zohuri B. Compact heat exchangers: Springer; 2017.
[16] Yunus CA, Afshin JG. Heat and mass transfer: fundamentals and applications. Tata McGraw-Hill, New Delhi, India. (2011).