Isı Bilimi ve Tekniği Dergisi, 30, 2, 69-76, 2010
J. of Thermal Science and Technology
©2010 TIBTD Printed in Turkey
ISSN 1300-3615

THE THEORETICAL AND PRACTICAL STUDY ABOUT INCREASING THE CAPACITY OF AUTOCLAVE HEAT EXCHANGER

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(Geliş Tarihi: 31. 09. 2008, Kabul Tarihi: 18. 12. 2009)

Abstract: Lamination process is the last step of the automobile windshield production which is carried out at the autoclave cabin by high pressure and temperature. First, raising of the temperature and pressure takes place. Then by means of cooling and air releasing the process is completed. In order to shorten the autoclave cycle time, the elements and operating parameters causing the variability in the autoclave cycle times has been analyzed according to the heat transfer laws. Design changes based on mentioned scientific analysis were evaluated as comparison. The best design was manufactured and implemented. The operating parameters of the autoclave were monitored both before and after the implementation of design changes. The implemented theoretical and practical study prove that decreasing the cooling time of autoclave 20% without loss of product quality is possible and can be repeated.
Keywords: Laminated auto glass, autoclave cycle, heat exchanger, lamination process

OTOKLAV ISI DEĞİŞTİRGECİNİN KAPASİTESİNİN ARTIRILMASI ÜZERİNE TEORİK VE PRATİK ÇALIŞMA

Özet: Otomobil ön camı üretim prosesinin son adımı, yüksek basınç ve sıcaklık odası şeklindeki otoklav içindeki otomobil camlarının laminasyon işlemidir. Bunun için önce otoklavın basıncının ve sıcaklığının arttırılması gerçekleştirilir. Sonra soğutma ve arkasından havanın dışarıya atılması ile süreç tamamlanır. Çevrim süresinin kısaltılması amacıyla otoklav çevrim süresinde değişkenliğe neden olan unsurlar ve işletme parametreleri ısı geçişi yasalarına göre analiz edilmiştir. Bunu esas alan tasarım değişiklikleri karşılaştırmalı olarak değerlendirilmiştir. En iyi ve en uygun olan tasarım imal edilerek devreye alınmıştır. Otoklava ait tüm tesisatın tasarım öncesi ve tasarım sonrası işletme parametreleri ölçülerek sonuçlar karşılaştırılmıştır.Yapılan teorik ve uygulamalı çalışmalar, hedeflenen ürün kalitesini düşürmeden, enerji yoğun tesisat olarak fonksiyon gören otoklavda, soğutma süresinin % 20 azaltılmasının olanaklı ve tekrarlanabilir olduğunu kanıtlamıştır.
Anahtar Kelimeler: Lamine otomobil camı, otoklav çevrimi, ısı değiştirgeci

Nomenclature

A_d	Outer surface area of tube (m^2)
A_i	Inner surface area of tube (m^2)
D_1	Inner diameter of tube (m)
D_2	Outer diameter of tube (m
d_{inner}	Thickness of autoclave inner wall (m)
d_{outer}	Thickness of autoclave outer wall (m)
$d_{insulation}$	Thickness of insulation material in between inner and outer walls of autoclave (m)
d_{jacket}	Wall thickness of cooling jacket (m)
F	Overall surface area of heat exchanger (m^2)
F_{jacket}	Overall surface area of cooling jacket (m^2)
h_i	Heat convection coefficient inside the tube (W/m^2K)
h_d	Heat convection coefficient outer side the tube (W/m^2K)
h_{air}	Heat convection coefficient of air inside autoclave (W/m^2K)
h_{water}	Heat convection coefficient inside cooling jacket (W/m^2K)
K	Overall heat transfer coefficient for heat exchanger (W/m^2K)
K_{jacket}	Overall heat transfer coefficient for cooling jacket (W/m^2K)
k_{water}	Heat conduction coefficient of water (W/mK)

k_{inner}	Heat conduction coefficient of autoclave inner wall (W/mK)
$k_{insulation}$	Heat conduction coefficient of insulation material (W/mK)
k_{air}	Heat conduction coefficient of air (W/mK)
k_{outer}	Heat conduction coefficient of autoclave outer wall (W/mK)
k_{jacket}	Heat conduction coefficient of cooling jacket (W/mK)
L	Length of finned tube (m)
$\Pr$	Prandtl number
$\Pr_s$	Prandtl number of air at surface temperature
Q	Heat transfer at heat exchanger (W)
Q	Heat transfer at cooling jacket (W)
Re	Reynolds number
R_f	Dirtiness factor for inner side of tube (m^2K/W)
R_t	Contact resistance in between cooling jacket outer surface and autoclave outer surface (m^2K/W)
R_f	Dirtiness factor at inner side of cooling jacket (m^2K/W)
r_1	Inner radius of tube (m)
r_2	Outer radius of tube (m)
t_{air}	Average air temperature inside autoclave (C)
$t_{waterinlet}$	Inlet cooling water temperature (C)
$t_{wateroutlet}$	Outlet cooling water temperature

Greek Symbols

ΔT_m	Average logarithmic temperature difference (K)
Δt_{jacket}	Temperature difference in between cooling water and average air temperature in autoclave (K)
η	Fin effectiveness
w	Velocity of water (m/s)
ϑ	Kinematic viscosity (m^2/s)
σ	: Density of air (kg/m3)
c_p	: Specific heat of air (J/kgC)
w	: Velocity of air (m/s)

INTRODUCTION

Automobile glasses which have safety and visual characteristics are in two group, laminated and tempered. While windscreens are laminated glasses, door glasses and back lites are tempered glasses. Laminated windscreens are manufactured by assembling of two glass panes which have flat or curved form. A Polivnly Butraly interlayer (PVB) is used to assemble two panes.

During the first step which is called as "pre lamination", PVB is placed in between two glass panes and heated up to 80-100 ˚C in a furnace then by press rolls the air in between PVB and glass is pushed out and edges of the glass are sealed. Second step is the "final lamination" which is carried out at the autoclave. In this step, PVB gets the fully transparent view and reach permanent adhesion to glass panes.

The purpose of the autoclaving is dissolving the residual air in the PVB and developing the adhesion between glasses. Air is penetrated in to the PVB by diffusion. Diffusion increases exponantialy by temperature and linearly by pressure and time. During autoclave cycle PVB is soften, gets fluid form and fills openings between PVB and glass. At the end of the autoclave cycle PVB gets the uniform thickness.

Depending on the product type, capacity utilization rate of autoclave and seasonal changes the autoclave cycle time vary in between 120 and 160 minutes. The purpose of this study is eliminating the variation of autoclave cycle time, therefore a new heat exchanger which eliminates above explained variations, designed, manufactured and put into service.

Autoclave Cycle

Autoclave cycle is the combination of temperature, pressure and time. Both for temperature and pressure has three steps: ramp up, hold and ramp down. Figure 1 shows the change of temperature and pressure for a typical autoclave cycle.

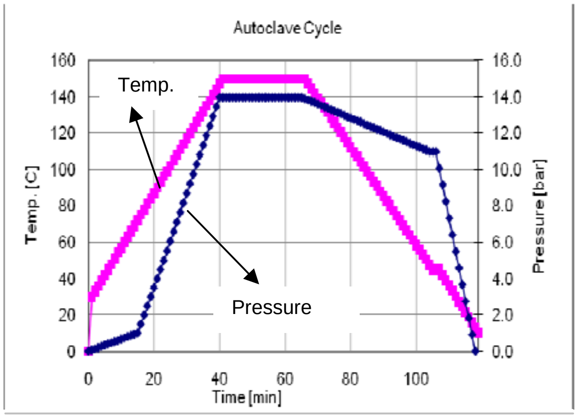


Figure 1. Autoclave cycle. Change of temperature and pressure versus time

During first step heat-up of the autoclave is done by electrical energy. At last step, cool down of autoclave is done by cooling water which is supplied from cooling tower. Cooling water is circulated in a heat exchanger in the autoclave. When the pressure is completely released to the atmosphere autoclave cycle is finished. Concerning the product quality, the pressure is not released before the temperature reach to 45 ˚C this is why if temperature reach to 45 ˚C longer than target then we say autoclave cycle is extended.

Autoclave has its own automatic control system both for temperature and pressure change. Controlling the temperature change properly inside the autoclave at ramp up step there are electrical control systems and to control the temperature change properly inside the autoclave at ramp down step the flow of cooling water is controlled via proportional valves.

In order to increase the pressure inside the autoclave during ramp up step an air flow is supplied from an air tank which has higher pressure than the autoclave maximum operating pressure. There is a piping between autoclave and air tank. Controlling the pressure change properly inside the autoclave both at ramp up and ramp down steps air flow is controlled via proportional valves. Figure 2 shows the components of autoclave process.

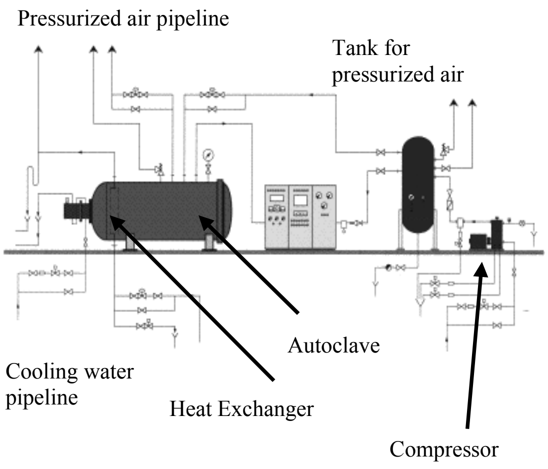


Figure 2. Components of autoclave (Scholz, 2003)

Observations on autoclave cycle show us that the undesirable cycle time change is due to extended cooling time to reach the safe temperature before pressure releasing. Cooling time vary according to the product type, capacity rate and seasonal changes. For a stable autoclave cycle time cooling system must be capable enough to meet different cooling loads.

IMPROVEMENT OF AUTOCLAVE COOLING CYCLE

Autoclave cooling cycle has two steps: "pre cooling" and "main cooling". Each cooling step has its own water circulation system including piping and proportional valves. In the beginning of the cooling cycle there is a risk of thermal shock and glass breakage due to the cooling speed. Pre cooling is low speed cooling cycle to eliminate risk of glass breakage due to thermal shock. Pre cooling cycle is finished automatically when the proportional valve reach its maximum flow rate. When the pre cooling cycle is finished main cooling cycle is started. [Scholz, 2003]

Defining Improvement Alternatives

Three different idea has been developed to improve the cooling cycle and evaluated concerning scientific principles. Those ideas are "installation of extra heat exchanger to autoclave", "installation of extra cooling system to the outer surface", "increasing the capacity of existing heat exchanger".

Installation of Extra Heat Exchanger to Autoclave

Extra heat exchanger will increase the cooling surface area thus heat transfer will increase and it could be possible to decrease or stable the cooling cycle. In order to get the maximum cooling surface area extra heat exchanger must be constructed by finned tubes.

Concerning the autoclave design and position of glasses inside it is possible to place the extra heat exchanger parallel to the air flow. Due to safety reasons it is not possible to enter extra piping to the autoclave this is why extra heat exchanger will use same piping with the existing heat exchanger.

The extra cooling capacity due to extra heat exchanger could be calculated by below statements. (Incropera, F. P. and Dewitt D. P., Fundementals of Heat ad Mass Transfer, Literatür , 51, 2001)

$$Q = KF\Delta T_m \tag{1}$$

The statement for overall heat transfer coefficient can be calculated as;

$$\frac{1}{K} = \left(\frac{1}{h_i}\right)\left(\frac{A_d}{A_i}\right) + R_f \frac{A_d}{A_i} + \frac{\ln(r_2/r_1)}{2\pi Lk} A_d + \frac{1}{\eta h_d} \tag{2}$$

Overall heat transfer coefficient is function of both inner and outer side heat convection coefficients and geometry. Heat convection coefficient for inner side (water side) of tube (h_i) can be found from below equations;

$$Nu = \frac{h_i D_1}{k_{su}} \tag{3}$$

Where Nu number can be calculated as a function of both Re and Pr numbers;

$$Nu = 0.023\,\mathrm{Re}^{4/5}\,\mathrm{Pr}^{1/3} \tag{4}$$

$$\mathrm{Re} = \frac{wD_1}{\vartheta} \tag{5}$$

Heat convection coefficient for outer side (air side) of tube (h_d)can be found from below equations;

$$Nu = \frac{h_d D_2}{k_{air}} \tag{6}$$

Where Nu number can be calculated as a function of both Re and Pr numbers;

$$Nu = C \operatorname{Re}^m \operatorname{Pr}^n \left(\frac{\operatorname{Pr}}{\operatorname{Pr}_s}\right)^{1/4} \tag{7}$$

It is necessary to know the water and air temperatures in order to calculate the average logarithmic temperature difference for heat exchanger. Since the air temperature inside the autoclave decreases throughout the cooling cycle, the system is not steady state. This is why the temperatures for water and air are average of values measured in the beginning and at the end of the cooling cycle. Average logarithmic temperature difference vary concerning the heat exchanger construction but if one of the temperature change of the fluids is negligible then it accepted that the logarithmic temperature difference is independent from heat exchanger construction (Incropera and Dewitt, 2001). The temperature difference of the air is negligible this is why average logarithmic temperature difference is calculated concerning the principle of "heat exchanger with parallel and reverse flow".

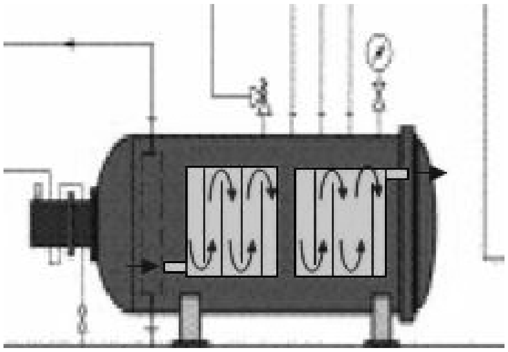
The statement for average logarithmic temperature difference:

$$\Delta t_m = \left[(t_{air} - t_{waterinlet}) - (t_{air} - t_{wateroutlet})\right] / \ln\left[(t_{air} - t_{waterinlet}) / (t_{air} - t_{wateroutlet})\right] \tag{8}$$

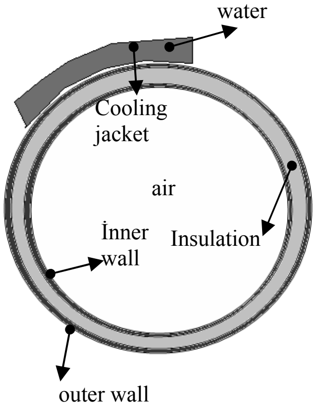
When the overall heat transfer coefficient and average logarithmic temperature difference is known the capacity of extra heat exchanger could be calculated. Installation of extra heat exchanger could supply additional cooling capacity which is % 25-30 of existing cooling capacity.

Installation of Extra Cooling System to Outer Surface of Autoclave

Installation of extra cooling system to outer surface of autoclave means that installation of a cooling jacket to outer surface of autoclave which will be activated in the beginning of the cooling cycle and which is fully independent from autoclave. Cooling water will be supplied to cooling jacket from cooling tower. An additional water pump will be used to circulate the cooling water inside the cooling jacket. Since the cooling jacket will only be active during cooling cycle and will be inactive during heating cycle the cooling water circulation pump will only run during cooling cycle. Figure 3. (a,b) Illustrate the installation of cooling jacket.



(a)



(b)

Figure 3. (a,b) Cooling jacket for outer surface of autoclave

Cooling capacity of cooling jacket can be calculated as;

$$Q_{jacket} = K_{jacket} F_{jacket} \Delta t_{jacket} \tag{9}$$

where overall heat transfer coefficient concerning the layers in between cooling water in the cooling jacket and air inside the autoclave can be calculated as;

$$\frac{1}{K_{jacket}} = \frac{1}{h_{air}} + \frac{d_{inner}}{k_{outer}} + \frac{d_{insulation}}{k_{insulation}} + \frac{d_{outer}}{k_{outer}} +$$

$$+ R_t + R_f + \frac{d_{jacket}}{k_{jacket}} + \frac{1}{h_{water}} \tag{10}$$

Due to the effect of insulation material in between outer and inner wall of the autoclave the overall heat transfer coefficient is calculated approximately 4 $(W / m^2 K)$ which cause less amount of heat transfer. Installation of extra cooling system to the outer surface could supply additional cooling capacity which is % 2 of existing cooling capacity.

Increasing The Capacity of Existing Heat Exchanger

The existing heat exchanger has three row finned tubes and the tubes are arranged in triangular order. It is possible to increase the cooling capacity of existing heat exchanger by adding one row of finned tubes. Adding the fourth row of tubes will decrease the velocity of the flow for per tubes this is why the heat convection coefficient will decrease at water side but extra cooling surface area will increase overall heat transfer on the heat exchanger.
The calculation method of the cooling capacity for the heat exchanger with increased capacity is same with the calculation method of the extra heat exchanger except the calculation of heat convection coefficient at outer side (air side) of the tube.

Calculation of heat convection coefficient at outer side (air side) of the finned tube (h_d) :

Concerning the design of the heat exchanger and the flow direction of the air the calculation of the heat convection coefficient must be done according to the principle of "cross flow to the tube group". Main item determining the flow characteristic and heat convection inside the tube group is "boundary layer conditions" (Incropera and Dewitt, 2001).

The heat convection coefficient for one tube is calculated concerning its location in the group. Whereas the heat convection coefficient of the tube which is located at first row is calculated concerning the principle of "cross flow to one tube", the tubes which are located at inner rows of heat exchanger have higher heat convection coefficient. The tubes located at first rows act as "turbulence grid" for coming tube rows (Incropera and Dewitt, 2001).

Considering the engineering problems it is desired to calculate the average heat convection coefficient for the tube group (Incropera and Dewitt, 2001).

Due to the fact that the heat exchanger of the autoclave has finned tubes it is a "compact heat exchanger".

Since there are many geometric item effecting the compact heat exchangers it is very difficult to find a statement to characterize the heat transfer. The studies on this issue are mainly experimental. The most comprehensive studies on this issue were done by Kays and London. They have grouped the different type of heat exchangers from certain manufacturers and documented the results by the graphics. (Genceli, 1999). At those graphics; Stanton number and Prandtl number which characterize the heat convection are given as a function of Reynolds number.

$$St.\mathrm{Pr}^{2/3} = f(\mathrm{Re}) \qquad (11)$$

$$St = \frac{Nu}{\mathrm{Re}.\mathrm{Pr}} = \frac{h_d}{\sigma c_p w} \qquad (12)$$

In order to calculate the average heat convection coefficient for heat exchanger of autoclave above mentioned graphics were used by choosing the most appropriate one (Genceli, 1999).

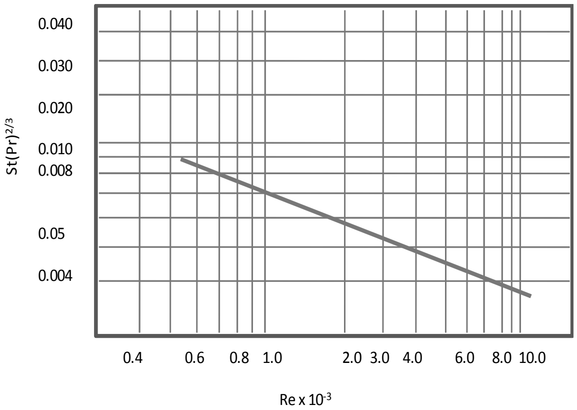


Figure 4. Air side heat convection coefficient for cross flow to tube group

Increasing the capacity of existing heat exchanger could supply additional cooling capacity which is 25% of existing cooling capacity.

Test, Installation and Start up of New Developed Heat Exchanger

Above described ideas which were developed to improve the autoclave cooling cycle have been evaluated concerning the feasibility principles and the idea of "increasing the capacity of existing heat exchanger" which is the most appropriate one have been implemented. Figure 5, shows the 3D view of new developed heat exchanger.

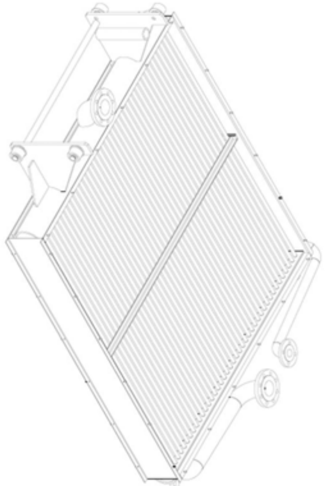


Figure 5. 3D view of heat exchanger

Before the installation of the heat exchanger it must be tested under 32 bar pressure which is higher 18 bar then the operating pressure. Due to the safety reasons pressure test could only be done by water. Below figure shows the applied test pressure to the heat exchanger.

Figure 6. Pressure test of the heat exchanger

Following the approval of pressure test heat exchanger is installed to the autoclave. Installation of heat exchanger has three steps:

- Disassembling of existing heat exchanger
- Installation of new heat exchanger
- Startup of installed heat exchanger (first trial)

To disassemble the existing heat exchanger first side covers of the exchanger and piping for the cooling water is dismantled. Then the heat exchanger is moved towards to autoclave door in vertical position and disassembling of heat exchanger is completed.

Installation method of new heat exchanger is similar but opposite to disassembling of the existing one. First heat exchanger is moved towards the backside of autoclave then piping water for cooling water and side covers are mantled.

RESULTS AND DISCUSSION

For a stable autoclave cycle time, the cooling system of the autoclave must be capable enough to meet the highest cooling load which is reached at maximum capacity rate.

Since, the cooling water is supplied from cooling tower its temperature changes depending on the outside weather temperature and the worst case occurs in the summertime.

For each improvement case the additional cooling capacity and total cooling capacity of the autoclave has been calculated according to the summertime conditions and listed in the table 1;

Table 1. Calculated additional & total cooling capacity of autoclave for each improvement case

	$Q_{additional}$ (kW)	Q_{total} (kW)
Existing cooling sys.		310
Extra cooling sys.	165	475
Outer surf. Cooling sys.	6	316
Increasing cooling capacity of existing sys.	140	450

The additional cooling capacity of each improvement case is dependent to total heat transfer coefficient and additional cooling surface area which are shown in the table 2;

Table 2. Calculated total heat transfer coefficient & additional surface are for each improvement case

	K (W/m^2K)	F (m^2)
Existing cooling sys.	73.40	134.50
Extra cooling sys.	24.10	96.40
Outer surf. Cooling sys.	2.50	37.60
Increasing cooling capacity of existing sys.	64.10	201.30

By means of above results, each improvement case evaluated comparatively and the case of “increasing the capacity of existing heat exchanger” was choosen and implemented, heat exchanger of autoclave was manufactured again by adding one more row of finned tubes and assembled to the autoclave.

The reasons for disapproved improvement ideas can be listed as follows; installation of extra heat exchanger to autoclave would cause the necessity of modifying the existing cooling water circulation system which is not desired, since the extra heat exchanger would use the same cooling water circulation system it would be difficult to balance the water flow for existing and extra heat exchangers which would cause the lack of capacity for both heat exchangers, due to the location of extra heat exchanger in the autoclave, circulated air inside could not get in touch with heat exchanger surface properly, installation of extra cooling system to outer surface of autoclave would eliminate the disadvantages of case of installing extra heat exchanger to autoclave but in that case it would not be possible to increase the existing cooling capacity significantly.

Performance of new developed heat exchanger has been followed by measuring the cooling cycle. New and previous cases have been compared by the graphics which are drawn by data recorder of the autoclave. Illustration of cycle graphics for new and previous cases is shown in figure 7&8.

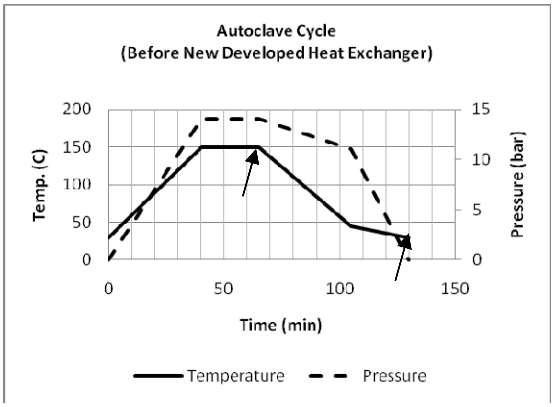


Figure 7. Autoclave cycle graphic before new developed heat exchanger

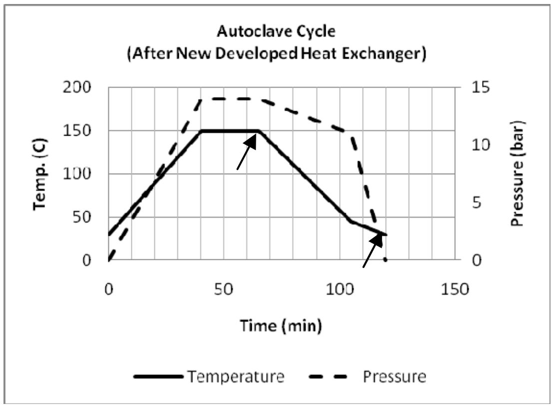


Figure 8. Autoclave cycle graphic after new developed heat exchanger

In the graphics the beginning and end of cooling cycle is marked by arrows. When the graphics are analyzed comparatively it is determined that after the implementation of new developed heat exchanger the cooling time is decreased from 65 minutes to 55 minutes and total cycle time is decreased from 130 minutes to 120 minutes.

REFERENCES

Scholz "Operating Instructions for Hot Air Autoclave", Scholz, 2003

Incropera, F. P. and Dewitt D. P., Fundementals of Heat ad Mass Transfer, Literatür , 51, 2001.

Genceli O. F., "Heat Exchangers", Birsen Publishing house, 1999

Parmaksızoğlu C. and Çeteci Ö., "Isı Değiştiricisi Tasarımı", 4. Ulusal Tesisat Mühendisliği Kongresi ve Sergisi Bildiriler Kitabı 135-147, 1999

Demir A. "Kanatlı Bir Isı Değiştiricisi İçin Optimum Dizayn Parametrelerinin Belirlenmesi", Atatürk Üniversitesi Yüksek Lisans Tezi, 2006

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