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Heat Transfer in Unitanks

In the following article the author summarizes his work on heat transfer in Unitanks. The engineering aspects involved in sizing cooling areas for a Unitank are discussed and the different inputs to be specified by the brewer and the designer, essential to arrive at a satisfactory solution, are listed. The implications of varying the inputs on the final result are explained with illustrations in specific cases. Basic heat transfer equations, theories involved and a stepwise procedure to solve the problem are included. Results from a computer based programme developed for this application are tabulated and the utility of such a model for an optimum solution is explained.

BC 53 Cold

(Descriptors: Cooling in breweries and maltings, heat transfer, unitank, one-tank process, convection.

Descriptoren: Kälteanwendung in Brauereien und Mälzereien, Wärmeübertragung, Unitank, Eintankverfahren, Konvektion).

1 Introduction

In a brewery, a Unitank, as the name implies, is used for fermentation, cooling and maturation in the same tank. From a heat transfer point of view for sizing the cooling areas, three different duty conditions come into the picture.

1. To maintain wort/beer at a constant temperature during the exothermic fermentation process.
2. To cool the green beer from fermentation temperature to the maturation temperature at a specific rate.
3. To maintain beer at a constant temperature during maturation. Usually under this condition, temperature rise due to heat gain is only to be arrested.

In most cases the heat duty specified under item number (2) is the controlling factor and is considered as the basis for calculating the cooling areas. The types of heat transfer involved are:

- Natural convection heat transfer inside the tank during cooling of the beer.
- Forced convection heat transfer outside the tank on the coolant side.

2 Inputs

To arrive at a satisfactory solution, it is essential that inputs from both the brewer and the designer are well specified since every input influences the final result. The various inputs are listed below and their implications on the final result are explained with illustrations.

Inputs by the brewer

- Tank working volume.
- Cooling conditions/duty.

  Most breweries desire a two stage cooling cycle. Typically cooling from the final fermentation temperature between 12 °C to 18 °C upto an intermediate temperature of 4 °C or 5 °C in 16 to 20 hours at a cooling rate between 0.5 °C/h to 0.8 °C/h in the first stage and then cooling from this intermediate temperature to a temperature of to 0 °C or -1 °C in 24 to 48 hours.

  Any change in this cooling duty will have a large influence on the cooling area requirement.
- Cooling medium supply temperature.

  From a heat transfer perspective, it is better to have a lower cooling medium supply temperature, however this may also cause the beer to freeze due to lower wall temperatures.

  The effect of the change in the cooling medium supply temperature on the time required for cooling is illustrated in fig. 1.

  With good automation and temperature controllers, systems are performing satisfactorily with cooling medium supply temperatures as low as - 6 °C.
- Type of cooling medium.

  This parameter influences the forced convection heat transfer owing to its thermal properties, i.e. the external heat transfer on the jacket side and thus has an effect on the cooling area

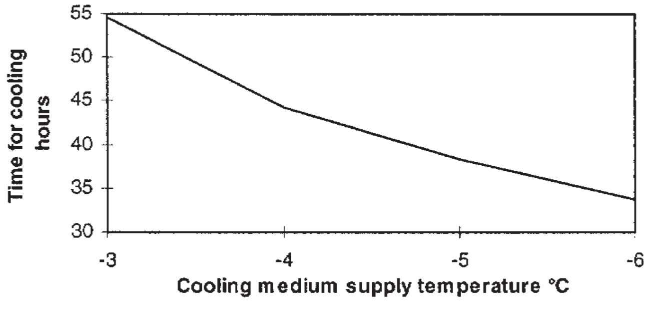

Figure 1 Effect of cooling medium supply temperature on cooling time

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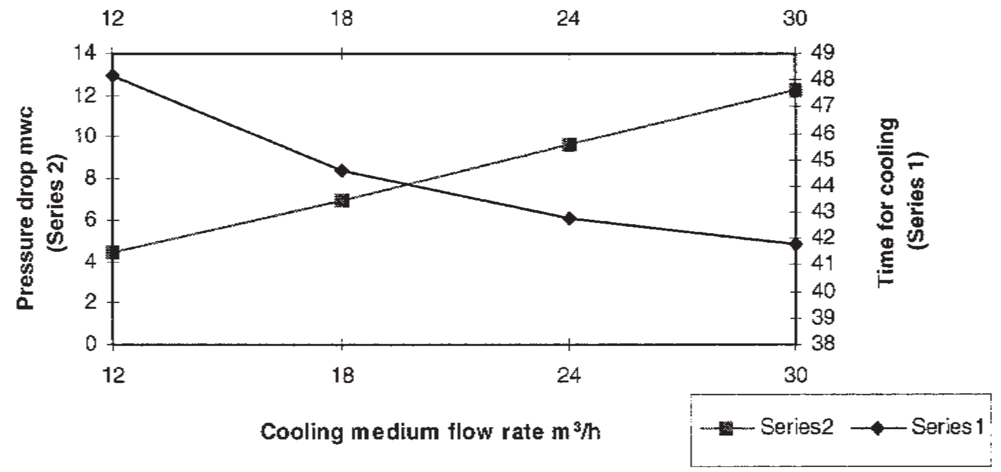

Figure 2 Relation between cooling medium flow rate, pressure drop & time required for coo-

to be provided.

- ☐ Maximum allowable flow rate and allowable pressure drop for the cooling medium.

  If there is a limitation in the cooling medium supply to the Unitanks as it can be in the case of modernisation or while increasing brewery capacity, the same shall be specified. However, in the case of a new brewery, the designer can himself select an optimum flow rate. It can be seen from fig. 2 that as the flow rate increases, the time required for cooling reduces, while the pressure drop and the power consumed by the refrigerant pump increases.

Inputs by the designer

- ☐ Cooling medium thermal properties.
- ☐ Beer thermal properties
- ☐ Assumed heat transfer area. As a rough approximation the following values can be considered for initiating the calculations. (For cooling medium supply at - 6 °C).

Cooling range	Area assumed m²/hl of tank volume
15 to 4 °C in 24 h and 4 to -1 °C in 12 h	0.09
15 to 4 °C in 24 h and 4 to -1 °C in 24 h	0.06
15 to 4 °C in 24 h and 4 to -1 °C in 48 h	0.05

However, it should be noted that these values serve only as a rough approximation and the actual heat transfer area is largely dependant on the various parameters and conditions mentioned hereunder.

- ☐ Heat transfer area (Assumed) on shell and the bottom cone.
- ☐ Number of cooling zones (Total)

  This figure has an implication on the velocity of the cooling medium through the cooling jacket and hence influences the heat transfer coefficient and the pressure drop on the jacket side.

- ☐ Maximum available cooling load

  As the heat transfer rate in the initial cooling range (between 15 to 8 °C) is higher, compared to the cooling ranges below 4 °C, it is possible with the given area for cooling, to reduce the time required for cooling the beer during the initial cooling range. However then in the initial cooling range the refrigeration load required is higher. Since the refrigeration plant is sized only on an average basis, it can become a limiting factor. Thus in order to achieve the desired cooling rate, either the refrigeration load during this range (Initial) or some value higher than the average load shall be considered. It should be noted that for every degree drop in the temperature of the beer, the time required for cooling varies and is not a constant value. Hence the refrigeration load requirement also varies. See figure 3.

- ☐ Jacket geometry

  This would decide the flow velocity of the cooling medium and, as mentioned before, would influence the heat transfer coefficient on the jacket side.

- ☐ Unitank geometry and material thicknesses.

  This is used to calculate the height of liquid in the Unitank and to check if the jacket top level is below the working volume and calculate the wall resistance.

3 Stepwise procedure

Step 1

Determine the heat load from basic heat transfer equation

$$Q = \frac{mcpdT}{\theta} \qquad \text{......... e1}$$

This is used to calculate the average refrigeration load and serves as a guideline to decide the peak cooling load.

Step 2

Calculate the cooling medium outlet temperature

$$Q = wCdT \qquad \text{......... e2}$$

Step 3

Application of the equation to calculate the time required for cooling the beer

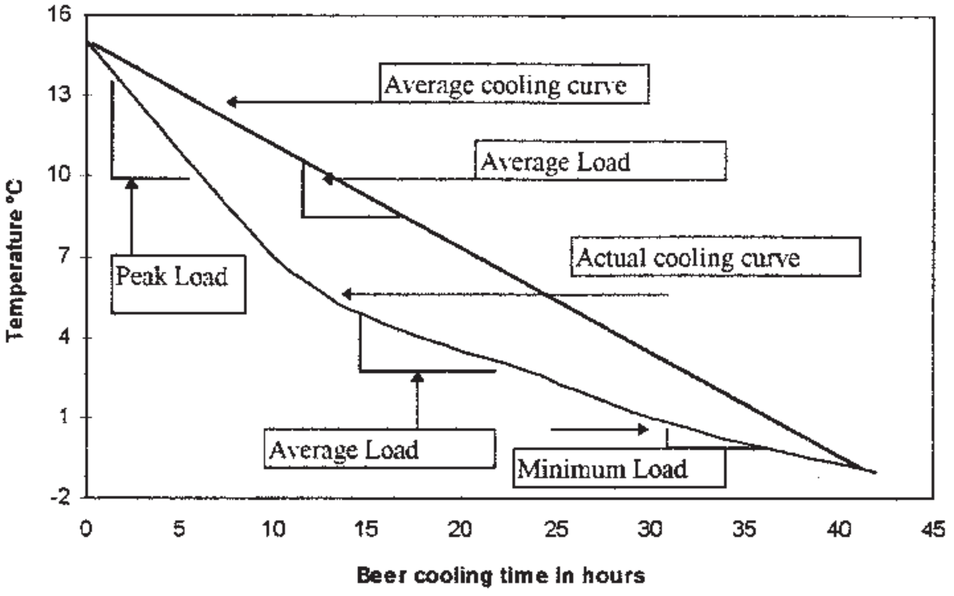

Figure 3 Time versus temperature

Many equations are available to predict the relationship between heat transfer area, the overall heat transfer coefficient, heat duty and the time required for cooling. But considering the dynamics of this cooling phenomenon the appropriate equation satisfying all the conditions is

$$\ln \left|\frac{t1 - T}{t2 - T}\right| = \left|\frac{wc}{mc_p}\right| \left|\frac{K - 1}{K}\right| \theta \qquad \text{......... e3}$$

Where $K = e^{UA/wc}$ e4

This equation is specifically applied to cases where the contents in a tank are cooled batchwise and where the inlet and outlet temperature of the cooling mediums are not constant. Since the cooling of beer in a Unitank is a classic example of a batch unsteady state type heat transfer, the above equation holds good for all practical calculations. Furthermore the factor K comes into the picture, since the difference between the cooling medium inlet and outlet temperature varies throughout the cooling range and is more than 10 % of the log mean temperature difference.

The above equation is based on the assumption that the U value remains constant throughout the cooling process. However, it is well established through practical observations and theoretical calculations that the U value varies significantly within the normal beer cooling ranges. (U varies from 50 Kcal/hm^2 °C to 150 Kcal/hm^2 °C). For the very fact that the U value varies so drastically, the cooling range has to be divided into small increments and the time required shall be calculated separately for each increment.

As the time required for cooling the beer varies depending upon the temperature range in which the beer is cooled, the outlet temperature of the cooling medium also varies. For this very reason the problem becomes more complex and needs to solved by iterations.

Step 4

Calculate the internal heat transfer coefficient

As this is a natural convection heat transfer phenomenon, it is obvious that the resistance due to this internal heat transfer coefficient is higher than the other resistances to heat transfer is the controlling one and would have the largest impact on the final results.

(Natural convection occurs when a solid surface is in contact with a fluid of a different temperature to the surface. Density difference in the contact fluid provides the body force or the driving force for the heat transfer by moving the fluid or generating convection currents for the fluid movement.) The general type of equation which can be applied to the case of Unitank is the Nusselt equation for vertical plates, and the generalised form of the equation can be represented as

$$\left|\frac{hl}{k}\right| = a \left|\frac{L^3 \rho^2 g \beta \Delta t}{\mu^2}, \frac{c_p \mu}{k}\right|^m \qquad \text{......... e5}$$

For vertical cylinders and plates the values of a and m in the above equation have been determined and the following relations are derived for $1 < N_{pr} < 40$.

For $N_{gr} > 10^9$ the following equation shall be applied

$$N_{Nu} = 0.138 N_{Gr}^{0.36} \left[N_{Pr}^{0.175} - 0.55\right] \qquad \text{......... e6}$$

0.25

For $N_{gr} < 10^9$ the following equation shall be applied

$$N_{Nu} = 0.683 N_{Gr}^{0.25} N_{Pr}^{0.25} \left|\frac{N_{Pr}^{0.175}}{0.861 + N_{Pr}}\right| \qquad \text{......... e7}$$

Step 5

Calculation of the external heat transfer coefficient

Since in all cases the flow of cooling medium is either turbulent or laminar in nature, standard equations for heat transfer coefficient for forced convection apply. The only care to be taken is to calculate the equivalent diameter for different jacket geometries.

Nomenclatures

Description		Units
a	Constants (Equation)	
A :	Area for heat transfer	m^2
Cp:	Specific heat – Beer	Kcal/Kg °C
C	Specific heat – Cooling medium	Kcal/Kg °C
de	Equivalent diameter for heat transfer	m
Dc	Coil diameter	m
dco	Outer diameter of cooling jacket	m
dcm	Mean diameter of cooling jacket	m
g	Gravitational constant	m/s^2
hfi	Fouling factor Shell side	Kcal/hm^2 °C -1
hfo	Fouling factor Jacket side	Kcal/hm^2 °C -1
hi	Internal heat transfer coefficient	Kcal/hm^2 °C
hfo	External heat transfer coefficient	Kcal/hm^2 °C
K	Thermal conductivity of beer	Kcal/hm °C
K	Thermal conductivity of tank material	Kcal/hm °C
l	Length of cooling jacket	m
L	Height of the cooling jacket	m
m	Mass of beer	Kg
m	Constants (Equation)	
Nre	Reynolds number	
Ngr	Grashoff's number	
Npr	Prandtl number	
Nnu	Nusselt number	
t	Glycol / Cooling medium temperatures	°C
T	Beer temperatures	°C
dT	Temperature difference	°C
U	Overall heat transfer coefficient	Kcal/hm^2 °C
w	Mass flow rate of cooling medium	Kg/h
x	Shell material thickness	m

Suffixes

1,2	Initial and Final conditions	
a,b	Initial and Final conditions	
Avg	Average	
ρ	Density	Kg/m^3
β	Coefficient of thermal expansion	1/°C
μ	Viscosity	cP or Kg/m-s
θ	Time required for cooling	h

$$\beta = \frac{\rho_a - \rho_b}{\left(\frac{\rho_a + \rho_b}{2}\right)}$$

$$\Delta t = T_{avg} - t_{avg}$$

(The equivalent diameter concept is applied when the geometry of the sections through which the fluid flows is not circular.) As the flow of fluid is not straight, but rather in spiral or circular form, the Sider Tate equation with coil correction can be applied.

For $N_{re} > 10{,}000$ (Turbulent flow)

$$\frac{h_j d_e}{k} = 0.027 N_{Re}^{0.8} N_{Pr}^{0.33} \left(1 + 3.5\left(\frac{d_e}{D_c}\right)\right) \quad \text{......... e8}$$

Step 6

Calculate the overall heat transfer coefficient

$$\frac{1}{U} = \frac{1}{h_i} + \frac{1}{h_o}\left(\frac{d_{co}}{d_{cm}}\right) + \frac{x}{k}\left(\frac{d_{co}}{d_{cm}}\right) + h_{fi} + h_{fo} \quad \text{............. e9}$$

Having known all the values and the assumed area for heat transfer, proceed further for calculating the time required for cooling.

Step 7

1. Divide the cooling range into small increments of 1 °C each.
2. Assume the time required for cooling.

For each increment

1. Calculate the coolant outlet temperature using equation e2.
2. Calculate the internal heat transfer coefficient using equation e6 or e7.
3. Calculate the external heat transfer coefficient using equation e8.
4. Calculate the overall heat transfer coefficient using equation e9.
5. Now calculate the time required for cooling using equation e3
6. Iterate the above two equations until the assumed time matches with the actual time for cooling.
   (Equations e2 and e3)

The results of the calculation are now obtained for each cooling range i.e. every 1 °C drop in temperature.

A computer aided programme to solve this problem, has been developed and typical results are also tabulated below.

4 Summary

As seen from the above, it is clear that variation of the inputs has a considerable impact on the final result. A computer model developed by the author for this application serves to arrive at an optimum solution. Since parameters like the cooling medium supply temperature, the cooling medium flow rate, and the jacket geometry influence the final result, a proper balance of these parameters leads to the most appropriate design, thus optimising power, initial investment, refrigeration plant capacity and the operating costs.

The author hopes that this article serves to provide an insight

Unitank

Working volume : 1320 hl

Heat transfer area : 93 m^2

Cooling medium supply temperature : -3 °C

Cooling range Temperature °C	Time required hours	Refrigeration loads TR
15 – 14	2.96	15
14 – 13	2.96	15
13 – 12	2.96	15
12 – 11	2.96	15
11 – 10	2.96	15
10 – 9	2.96	15
9 – 8	2.96	15
8 – 7	2.96	15
7 – 6	3.24	13.7
6 – 5	4.04	11.0
5 – 4	5.95	7.4
4 – 3	7.11	6.2
3 – 2	6.83	6.5
2 – 1	7.77	5.7
1 – 0	10.21	4.3
0 – -1	12.0	3.5
Total	80.84	

into the inputs needed as a basis of design and the impact of various parameters explained would be helpful while designing a Unitank.

5 Zusammenfassung

Varma, R. R.: Wärmeübertragung in Unitanks — Monatsschrift für Brauwissenschaft 52, Nr. 1/2, 4 – 8, 1999

BC 53 Kälte

In folgendem Artikel faßt der Autor seine Arbeit zur Wärmeübertragung in Unitanks zusammen. Es werden die technischen Aspekte im Zusammenhang mit der Dimensionierung der Kühlflächen für einen Unitank erörtert und die verschiedenen, durch den Braumeister und den Konstrukteur festzulegenden Zufuhrmengen aufgelistet, die für eine befriedigende Lösung entscheidend sind. Die Auswirkungen von Änderungen der Zufuhrmengen auf das jeweilige Endergebnis werden in bestimmten Fällen anhand von Illustrationen erläutert. Hinzu kommen die Grundgleichungen zur Wärmeübertragung, die einschlägigen Theorien und ein Schritt für Schritt beschriebenes Verfahren zur Problemlösung. Außerdem werden die Ergebnisse eines für diese Anwendung entwickelten Computerprogramms tabellarisch aufgeführt, und der Nutzen eines solchen Modells für eine optimale Lösung wird erläutert.

Varma, R. R.: Transfert de chaleur dans les Unitanks — Monatsschrift für Brauwissenschaft 52, Nr. 1/2, 4 – 8, 1999

BC 53 Froid

L'auteur résume dans l'article qui suit son travail sur le transfert de chaleur dans les Unitanks. On décrit les aspects techniques en liaison avec le dimensionnement des surfaces de refroidissement pour un Unitank. De plus on a listé les différentes quantités d'alimentations préetablies par le maître-brasseur et le constructeur et qui sont décisives pour une solution satisfaisante. Les conséquences d'un changement de la quantité d'alimentation sur le résultat respectif final sont commentées dans des cas précis par des illustrations. A cela s'ajoute des formules de base sur le transfert de chaleur, les théories correspondantes et une procédure pas à pas pour la solutions de problèmes. D'autre part on aborde les résultats d'un programme informatique développé pour cette application sous forme de tableaux et l'utilité d'un tel modèle pour une solution optimale.

6 References

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3. Heat transfer by D Q Kern.
4. Unit operations of chemical engineering by Mcabe Smith. 6 References.

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