ENERGY ANALASIS OF COOLING SOURCES IN DISTILLATION COLUMN

Tomáš HOLOTA[1], Mária HOLOTOVÁ[3], Ján CSILLAG[2], Matúš BILČÍK[2], Peter KUCHAR[1]

[1]Institute of Agricultural Engineering, Transport and Bioenergetics, Slovak University of Agriculture in Nitra, Faculty of Engineering, Tr. A. Hlinku 2, 949 76 Nitra, Slovakia
[2]Institute of Electrical Engineering, Automation, Informatics and Physics, Slovak University of Agriculture in Nitra, Faculty of Engineering, Tr. A. Hlinku 2, 949 76 Nitra, Slovakia
[3] Institute of Marketing, Trade and Social Studies, Slovak University of Agriculture in Nitra, Faculty of Economics and Management, Tr. A. Hlinku 2, 949 76 Nitra, Slovakia

Abstract
The world is making great progress in technological field, and this is exactly what create new opportunities to reduce costs. One of the ways is to design an appropriate cooling of the distillation column, which ultimately contributes to positive economical results in distillery operating. The aim of the article is to propose the most efficient cooling method in distillation. The cooling sources described in the methodology were selected on the basis of cooling water flow measurement, implementation costs and annual operating costs. This data was evaluated by using the FDMM method. We found out by a more detailed comparison that at a flow of 400 m3 per year it is most worthwhile to cool with public water system until the fourth year of operation. From the fourth year of operation, cooling costs are lower at a given flow rate if we use a pumped groundwater with a frequency converter or pressure tank.

Key words: *distillation, cooling, distillation column, cooler.*

INTRODUCTION
Distillation equipment are used in the food industry as well as in the chemical industry in ethanol distillation process from prepared fermented mash (*Vogelpohl, 2015*). For these processes various distillation methods are used as well as different related distillation technologies. In the case of the use of distillation equipment in the food industry, the primary focus is on the processing of mash prepared from fruit and agricultural crops. Ethanol from agricultural crops can be divided into consumable and bioethanol as an ecological fuel additive (*Turner, 2006*).In the food industry, two basic types of distillation equipment are used, namely a double distillation boiler and a distillation column (*Holota, 2019*).
Quality and effective distillery equipment provide a prerequisite for ensuring proper production techniques and the opportunity to consume quality spirits for the wide public. These processes are greatly influenced by the correct choice of distillation equipment (*Holota, et al., 2021*). The technological equipment of distilleries must be also adapted to the requirements of growers, who process fruit and agricultural crops (*McHarry, 2012*). The input costs represent a costly item for each organization at the establishment of the distillery. The current requirement for quality products in the best price range, encourages distillery owners to find the most efficient ways to operate them. One of the ways is selected method of cooling during distillation. The profitability of the process and time-acceptable return on input costs can only be achieved by using the device effectively. One such way to reduce costs is to apply the most efficient cooling in distillation equipment while maintaining the quality of the final distillates.
The purpose of cooling is to remove heat from materials or liquid substance, which are either cooled to a temperature lower than the surroundings, or their state changes, or reaction heat is removed (*Clark, 2008*).The vapors from the distillation pot pass through the vapor pipe and enter the cooler. The task of the cooler is to condense these vapors and cool down to a temperature of 10°C to 20°C. The temperature of the distillate flowing out of the cooler should be the same or just a little higher than the cooling water temperature (*Opáth, 2007*). Cooling is a very important element that affects the result of the distillation process in a fundamental way. It is important not only to choose the right volume of the cooler, which depends on the distillation pot volume but also the type of distillation equipment (*Fekete, et al., 2007*).

In the presented paper, we emphasized the reduction of energy consumption of the production of fruit distillates and therefore the main aim of the study was to propose the most efficient cooling method in distillation.

MATERIALS AND METHODS

The research is focused on various types of cooling medium in the coolers of distillation column with a nominal volume of 300 l. The measurements were carried out on 3 identical distillation equipment with the same amounts per distillation batch (i.e. 300 l of fruit mash) at the same time.
One distillation process of 300 liters of mash takes 3 hours, using a coolant with an inlet temperature of 12°C and a coolant volume of 205 liters per production batch of 300 liters of mash. It is possible to process up to 2400 liters of mash in 8 batches within 24 hours.

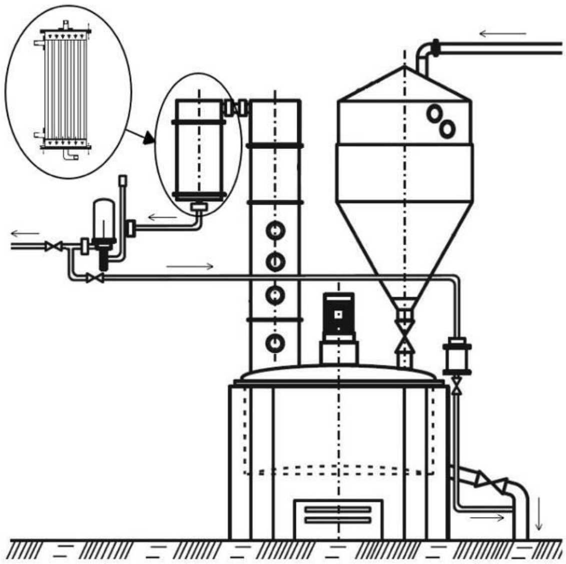

Fig. 1 Schematic diagram of distillation column with tube cooler

A tube exchanger/cooler is installed on the distillation equipment (see Figure 1). The cooler has 4 holes, where 2 serve for the inlet and outlet of the coolant and other 2 serve as the inlet of distilled vapors and the outlet of condensed distillate. Tube heat exchangers are the most common type used in industry. The tube diameters vary from 0.625” to 1.5” (~16 mm to 38 mm) in conventional heat exchangers. These heat exchangers have very low surface area to volume ratio. Since this type of heat exchanger can handle more severe conditions and higher pressures and temperatures, it can be used in differently systems if there is no space limitation (*Chordia, et al., 2017*). The tube cooler is one of the most effective coolers as regards consumed amount of cooling medium required for the condensation of vapors produced during distillation and at the same time contributes to a higher quality of the final distillate (*Pischl, 1997*). Three basic sources of cooling medium were involved in the research. In the case of using underground water sources, we compared two methods of obtaining water, namely by using a pump with pressure vessel and by using a pump with a frequency converter. Based on selected cooling sources, we created the following research elements (Tab. 1). The temperature of coolant supplied to the cooler was the same for all cooling sources, namely 12°C. We ensured the same inlet temperature due to the relevant results of comparing the volume of consumed coolant from various sources during distillation. The temperature of 12°C was ensured with the mixing valve at the entrance to the cooler. It is an automatic valve for coolant control with return flow to the dephlegmator. The mixing valve can be adjusted in the range of 10°C to 80°C.

Tab. 1 Characteristics of research elements

Research elements			
V1	V2	V3	V4
Water from public water supply	Groundwater with using a pump and frequency converter	Groundwater with using a pump and a pressure vessel	Coolant with using a cooling tower
Water connection water meter shaft 10 micron filter siliphos filter	20 m well bore water meter shaft submersible pump Pedrollo 4SR 4/14 frequency converter GD10 pressure sensor tank ZILMET 24 liter 10 micron filter 6x siliphos filter stainless particulate filter plastic plate particulate filter	20 m well bore water meter shaft submersible pump Pedrollo 4SR 4/14 stainless steel tank 500l Aquatrading AISI 304/500 10 micron filter 6x siliphos filter stainless particulate filter plastic plate particulate filter	cooling tower PMS 9/85 K12 ATT BIF Pump 0,55 kW Electroinstalation, pipe connection Water chemical treatment

When comparing cooling sources, we applied the multi-criteria FDMM method (Forced Decision Matrix Method) with the following procedure (*Holota, et al., 2021*):

1. Determine the compared properties (criteria) of cooling sources and write them in the table.
2. Carry out a pairwise comparison of the criteria in a matrix plotted in tabular form. When comparing, rate the more significant criterion as "1" and rate the less significant criterion as "0".
3. Based on the criteria comparison, determine the appropriate weights for the criteria.
   $$weight_n = \frac{\sum_{n=1}^{n} H_n}{\sum_{k=1}^{k}\sum_{n=1}^{n} H_n}, - \quad (1)$$
   kde: H_n - evaluation of the criterion,-;
   n - number and ordinal number of the criteria;
   k - ordinal number of the evaluation of the criterion.
4. Create a decision matrix for separate assessment of materials and individual criteria.
5. Compare variants with regard to a specific criterion. We rate a more suitable variant as "1" and worse as "0".
6. Define the respective ratings using the equation based on the comparison of the variants:
   $$H_v = \frac{\sum_{i=1}^{i} H_{vi}}{\sum_{j=1}^{j}\sum_{i=1}^{i} H_{vi}}, - \quad (2)$$
   kde: H_{vi} - evaluation of the variant,-;
   i - number and ordinal number of the variant;
   j - ordinal number of the evaluation of the variant.
7. Create a decision table from the received weights and evaluations of the variants.
8. Define the weighted sum (S_v) using the equation:
   $$S_v = \sum_{n=1}^{n} weight_n \times H_v, - \quad (3)$$
   kde: $weight_n$ - weight value,-;
   H_v - variant value,-;
   n - number and ordinal number of the criteria.
9. Determine the order of the variants based on the calculated weighted sum.

RESULTS AND DISCUSSION

Cooling as the final process in the distillation of fruit distillates is carried out in tube coolers, by using 4 various cooling sources. In the first phase, we focused on the economic effectiveness of individual cooling sources, what can be seen in Figure 2, where cumulative price increase for procurement and operation in years is displayed while keeping the prices in 2021 and an average coolant flow rate of 400 m3/year. In the first year of operating costs, the input prices for the construction of individual cooling sources are also included according to the equipment price survey and the average price per 1 m3 of water in the year 2021. The lowest price of construction and the first annual operation, i.e., €1,640.56 can be seen in the case of using public water supply (potable water) and the highest €7,484.55 in the case of using a cooling tower. A very important moment occurs in the 4th year, when so far, the cheapest variant using public water supply is priced higher than the well source of cooling even with using both a tank and a frequency converter.

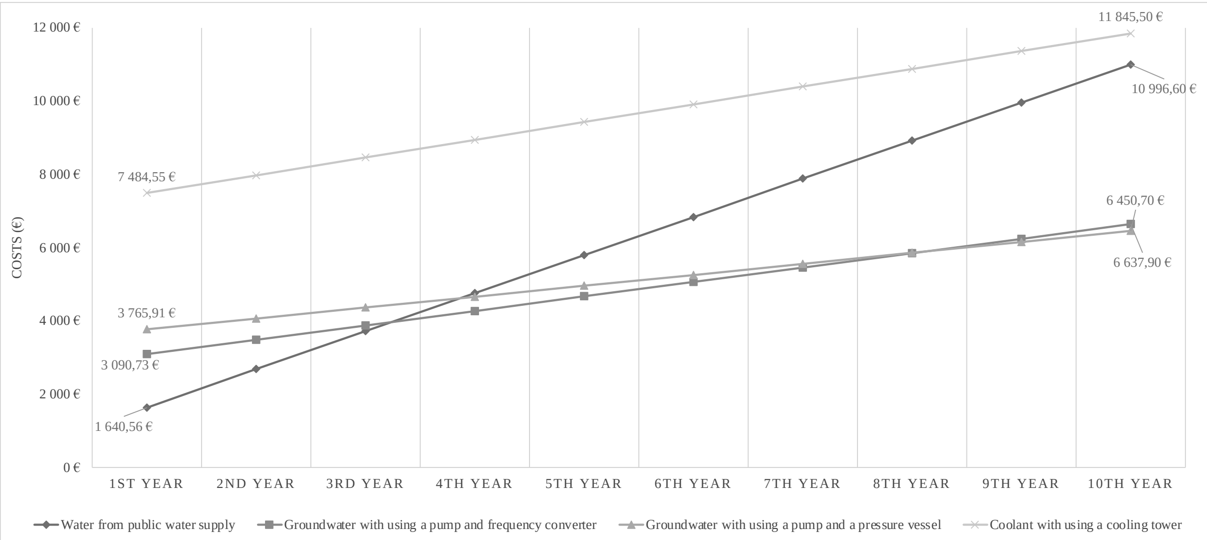

Fig. 2 Economy effectiveness of cooling sources

In the second phase, we focused on applying the multi-criteria method FDMM (Forced Decision Matrix Method) according to the procedure described in Materials and Methods. We decided on the FDMM method based on the requirement to eliminate subjective interventions into the process of choosing the most effective and efficient cooling source. At first, we proceeded to determine the weights using a pairwise comparison of criteria (establishment – K1, operating costs – K2, eco-friendly – K3, effectiveness – K4) in Table 2.

Tab. 2 Pairwise comparison of criteria

Criteria	K1	K2	K3	K4	Sum	wise
K1 – establishment	-	0	1	1	2	0,333
K2 – operating costs	1	-	1	1	3	0,500
K3 – eco-friendly	0	0	-	1	1	0,167
K4 – effectiveness	0	0	0	-	0	0,000

We applied a similar evaluation procedure in variants evaluation of cooling source for each selected criterion separately. We evaluated the compared variants of cooling sources "1" if it suited better the selected criterion, if it suited worse, we rated it "0". Pairwise comparisons of the variants were recorded in tables 3-6. We recorded pairwise comparisons of variants (V1 - Water from public water supply, V2 - Groundwater using a pump and a pressure vessel, V3 - Groundwater using a pump and frequency converter, V4 - Coolant using a cooling tower) in Tables 3-6.

Tab. 3 Pairwise comparison of variants according to criterion K1

Variant	V1	V2	V3	V4	súčet	váha
V1	-	1	1	1	3	0,500
V2	0	-	1	1	2	0,333
V3	0	0	-	1	1	0,167
V4	0	0	0	-	0	0,000

Tab. 4 Pairwise comparison of variants according to criterion K2

Variant	V1	V2	V3	V4	súčet	váha
V1	-	0	0	0	0	0,000
V2	1	-	1	1	3	0,500
V3	1	0	-	1	2	0,333
V4	1	0	0	-	1	0,167

Tab. 5 Pairwise comparison of variants according to criterion K3

Variant	V1	V2	V3	V4	súčet	váha
V1	-	0	0	0	0	0,000
V2	1	-	1	0	2	0,333
V3	1	0	-	0	1	0,167
V4	1	1	1	-	3	0,500

Tab. 6 Pairwise comparison of variants according to criterion K4

Variant	V1	V2	V3	V4	súčet	váha
V1	-	1	1	1	3	0,500
V2	0	-	0	0	0	0,000
V3	0	1	-	0	1	0,167
V4	0	1	1	-	2	0,333

Tab. 7 Decision table of the FDMM method

Criteria	Weight	Evaluated variants of the material			
		V1	V2	V3	V4
K1 – establishment	0,333	0,500	0,333	0,167	0,000
K2 - operating costs	0,500	0,000	0,500	0,333	0,167
K3 – eco-friendly	0,167	0,000	0,333	0,167	0,500
K4 – effectiveness	0,000	0,500	0,000	0,167	0,333
Weighted sum		0,167	0,417	0,250	0,167
Rank		3.	1.	2.	3.

As we can see from table 7, after taking into account the weights and values of individual variants using the weighted sum, we get a clear determination of the order of individual variants of cooling sources. Cooling using a pump and frequency converter is in the first place in the rating. Both cooling with water from public water supply and cooling with a closed cooling tower system are in the third place, their position was significantly affected by higher operating costs in the case of potable water and higher procurement costs in the case of a cooling tower. Based on the results of the FDMM method we decided that the most effective source of cooling in a still with a nominal volume of 300 liters is cooling provided by groundwater using a pump and frequency converter, which will ensure the fluidity and stability of the flow of coolant to the cooler. In the case of the FDMM method, we are talking about a modified decision matrix (FDMM - Forced Decision Matrix Method). The decision matrix provides an effective way to prioritize a particular item among many competing items. It's a process where we compare items on an individual base, on every other item with preference given to one over the other. Prioritization is defined according to weights (*Bhushan & Kanwal, 2004*).

CONCLUSIONS

Distilleries currently have high-level technological equipment. Just like any business, distillery also tries to manage its finances as the most effective as possible. In this step, it is important to determine how and where the economic costs can be minimized and thus ultimately make the work of the distillery more efficient. Currently, companies are trying to achieve a greater degree of sustainability and thus, in addition to the economic side, they must also focus on greater eco-friendly production and workplace processes in the company. The aim of the study was to propose the most efficient method of cooling during the distillation of fruit distillates in distilleries with a nominal capacity of the raw material boiler of 300 liters. In the first step, we visualized the economic side of individual cooling sources from their establishment to operation with a 10-year development prediction. The lowest initial costs together with operating costs in the first year were in the case of using public water supply and potable water, on the other side, the highest input costs together with operating costs were with the cooling tower. When we analyzed the ecological aspect of individual cooling sources, we can conclude that the use of potable water for cooling is the worst option from an ecological point of view.

When choosing the most appropriate cooling, we set criteria important for the right selection and applied the multi-criteria statistical method FDMM. The method showed that the most effective cooling of the distillation column at the determined flow rate is using groundwater transported by a pump with a frequency converter. This cooling method is also the most economically effective from the 4th year of operation, and until in the 9th year changes its position with groundwater transported by a pump with a pressure vessel.

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Corresponding author:

Ing. Mária Holotová, PhD., Department of Marketing and Trade, Faculty of Economics and Management, Slovak University of Agriculture in Nitra, Tr. A. Hlinku 2, Nitra, 949 76, Slovakia, phone: +421 907 560 780