Practical Approach to Optimal Cooling System Design for a Production Line Consisting of Plastic Injection Moulding Machines in Polish Specific Climat Conditions

doi:10.2478/mape-2020-0010
Date of submission to the Editor: 03/2020
Date of acceptance by the Editor: 06/2020
MAPE 2020, volume 3, issue 1, pp. 116-127

Maciej Bernacki
Schiessl Polska, **Poland**

Piotr Kaminski
ORCID ID: 0000-0003-1442-2047
Gdynia Maritime University, **Poland**

INTRODUCTION

Nowadays, the number of uses of plastics increases noticeably in many aspects of our life. Practically with each consequent year the next group of products which the raw material base was before: metals, wood or ceramics is dominated by synthetic materials. This result increased in serial production these elements with increasingly better quality, strength and aesthetic parameters.

The growth of this segment of world market impact on the manufacturers of such elements who want to stand out on the market are looking for technology that ensures maintaining the highest possible technical parameters at the lowest production costs at the same time. The manufacture investor at the investment phase (building a production plant and equipping it with a technological line) should take into account very large variability of plastic types being processed and the specificity of a given machining process what causes the necessity for quick and uncomplicated adaptation of the machine park to new product requirements.

The processes related with the injection moulding of plastic components can be optimized in several respects. Beyond the criterion of cooling system effectiveness other aspects were considered such as investment costs of specific type of the system, flexibility of the system allowing for quick and easy adaptation of the technology to various materials being processed or simultaneous operation of several injection moulding machines at different temperature parameters. Equally important aspects that have been taken into account are the currently binding and soon to come into force legal acts that significantly complicate the conduct of business activities and impose numerous obligations on manufacturers operate the refrigeration systems. The most important of them are the F-Gases Act of 15 May 2015 and related Regulation (EU) No 517/2016 of the European Parliament and of the Council of 16 April 2014 on fluorinated greenhouse gases impose the obligation of central records of refrigeration equipment, regular maintenance and survey of their tightness

Contact address: p.kaminski@wn.ueg.edu.pl

with a frequency depending on the content of carbon dioxide equivalent in the system and finally a prohibition of use the refrigerants with a potential for generating a warming effect (GWP – Global Warming Potential) above 2500 (Regulation, 2014).

COOLING SYSTEMS USED IN INDUSTRY

Over the years the process cooling technology has gradually changed from very simple, inefficient and difficult to maintain systems into specialized systems with high efficiency.

System using groundwater

System using groundwater was one of the oldest, simplest and easily available solution used for process cooling related to plastic by injection moulding. This medium has a very important property – the specific heat equals 4187 J/(kg·K), which is one of the largest in nature and is generally available, non-toxic and non-explosive. However many years' experience revealed many disadvantages of applications using groundwater, such as:

- low water evaporation temperature at atmospheric pressure (+100ºC),
- freezing temperature too high (0ºC),
- intensive scale formation (+60ºC),
- requirements of permits for water wells over 30 m deep,
- requirements of permits when extraction more than 15 m^3/day,
- additional fees for the economic use of the environment,
- necessity to cool down the water before release if the set value is exceeded,
- necessity to locate the plant at a reasonable distance from the river.

Over the years, collected experience, economic analysis and increasing formal and legal complications, groundwater-based systems lost popularity and were replaced by closed systems working on specialized heat transfer medium.

System based on a central liquid chiller

System based on a central liquid chiller is the leading solution of the cooling systems for plastic injection moulding processes. This refrigeration compressor coolers also called chillers or ice water aggregate. Depending on the plant configuration there may be a system with one chiller and multiple injection moulding machines or system with more than one chiller.

At present the most commonly used for liquid chillers are synthetic substances from the HFC group (refrigerants – hydrofluorocarbons – with Zero Ozone Depleting Potential (ODP) and average GWP index) generally known as "freons", where the most popular are R410A, R407C and R134a. As well as water solutions of ethylene or polypropylene glycols with correct concentration.

The advantage of the solution with a central water chiller is compact design, relatively simple installation and a wide range of temperature control. However the significant disadvantages are the necessity to keep the medium temperature low throughout the entire main line for the needs of selected units (e.g. only one of the injection moulds machine). It makes the whole system work inefficiently the aggregate consumes much more electricity than it results from the actual demand for cold. In the investment aspect it is one of the most expensive solutions. In addition, central chillers have a large refrigerant charge, which obliges registration of them in the central operators’ register of refrigerants, conducting regular leakage tests and records of all service activities.

Two-circuit system using a drycooler and a central water chiller

Many years of experience related to operation and the growing pressure on production economics influenced to more thorough analysis of individual refrigeration processes occurring during the operation of injection moulding machines in terms of manufacturing process optimization. A separation of the hydraulic oil cooling system from the mould cooling system was made. It resulted from the fact of very large temperature differences for each of these tasks, where providing them from the position of one compressor device would be inefficient. The rationalization consisted in associating the injection mould cooling system requiring a medium with a temperature around +15ºC with a water chiller, while the hydraulic oil cooling system for which the coolant temperature is sufficient at +40ºC with a drycooler.

A noticeable saving results from the fact that to maintain glycol at +40ºC practically whole year round, it is sufficient to use outside air as a coolant. This treatment called free-cooling carried out in appropriately selected drycoolers provides energy savings of up to 90%. Statistically, it can be assumed that dry-cooler fans consume ten times less electrical power compared to refrigeration compressors installed in water chillers. The investment cost is slightly higher than in the case of a system based solely on chilled water, however the difference in electricity consumption in favor of a solution with a separate cooling system is so large that it usually compensates after 24 months of use and in the following brings measurable savings.

In addition the optimization aspect in terms of operating costs, the hardware configuration provides much greater safety as to the continuity of production. Failure, downtime or service of one of the cooling circuits has no significant effect on the other what allowing to continue working of system. Each of the cooling subsystems in terms of hydraulics, power supply and control is a completely independent.

This solution is burdened with several disadvantages, which include, first of all: the obligation to register the water chiller in the COR base, which entails additional costs and operator responsibilities; moreover need to maintain a sufficiently low temperature in the main cooling line, require to build two pipelines, where the one related to mould cooling must additionally be insulated.

System using portable chillers and a central adiabatic drycooler

This is a system that takes into account all necessary required parameters and takes expected criteria where each injection moulding machine is equipped with an individual bench refrigeration units with a glycol-cooled plate condenser. Condensers as well as oil coolers are cooled from the glycol-main line. Then glycol after absorbing heat from both heat exchangers goes to the external drycooler equipped with an additional sprinkler system. Through to the use of individual micro-refrigerators for cooling injection moulds machines with a small charge of R407C refrigerant, there is no obligation to register devices in the COR database. And in the fact that each machine is equipped an individual thermostat allows that it can work in its optimal temperature range. The system is much more effective compared to the previous systems, where the temperature of the coolant in the main collector had to be lowered often for selected devices requiring the lowest cooling temperatures. Another advantage is oil cooling using a drycooler equipped with a sprinkler system that ensures that the glycol temperature is maintained at a level not exceeding + 30ºC even at an outside air temperature of + 35ºC. This is particularly important in the fact that the same coolant serves for the reception of heat from condensers of portable chillers. The lower the temperature of the condenser cooling medium, the lower the temperature of the condensing process and thus the higher the COP (Coefficient of Performance - it is the ratio of the cooling power generated by the compressor to the power consumed by it). In addition micro-refrigerators have a built-in automatic switching function to the free-cooling option where in the outside temperature below +10°C, glycol cooled to +15°C directly absorbed the heat from the injection moulds by-passing the compressor's refrigeration system. This gives measurable savings in energy consumption and reduces the level of generated noise. Such is shown in Figure 1, where, for example an injection moulding machine with an individual bench cooler was associated with one drycooler equipped with a spraying system.

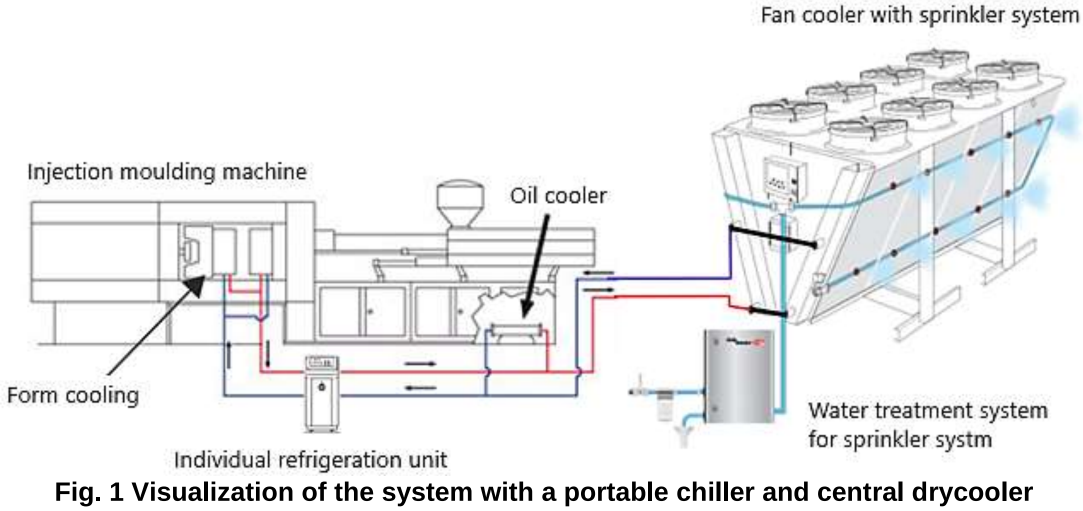

Fig. 1 Visualization of the system with a portable chiller and central drycooler

Source: (Bernacki, 2018)

Short comparison of presented systems

A comparative assessment of the presented systems was carried out where aspects relevant from the point of view of the oil cooling and form in the process of plastic processing by injection mould (Table 1). These are both technical issues affecting the long-term, failure-free operation of the system, simplicity of system construction and flexibility of operation as well as financial and legal aspect. The latter include primarily installation costs and the obligation to register devices in the CRO.

Table 1 Overall assessment of cooling systems

Variant of the system	Overall rating
Variant 1 System using groundwater	Simple system for conditions where processed materials require similar temperatures of cooling medium
Variant 2 System based on a central liquid chiller	An expensive system that gives some flexibility for conditions where processed materials require similar temperatures of cooling medium
Variant 3 Two-circuit system using a drycooler and a central water chiller	An expensive system, giving some flexibility for conditions where processed materials require similar temperatures of cooling medium, providing measurable savings in connection with the use of free-cooling
Variant 4 System using portable chiller units and a central drycooler with a adiabatic system	Moderately expensive system, giving full flexibility of temperature settings, providing measurable savings in connection with the use of free-cooling to cool oil and moulds form

Source: (Bernacki, 2018)

Due to the very high complexity of issues related to the refrigeration system, the study based on the experience and literature there was selected the following comparative criterions:

- consumption of cooling medium,
- processed medium does not cause scale deposits in pipes and heat exchangers, maintaining the flow efficiency at the same level, through to which the heat reception does not change over time,
- the cooling medium is not contaminated,
- oil is cooled with medium at ambient temperature,
- moulding forms are cooled with water solution of glycol at the same temperature,
- temperature adjustment of the fed medium into the moulding form can be done by throttling the flow or by means of a thermostat,
- system requires two circuits: insulated and thermally not insulated,
- possibility of energy-saving winter operation using free-cooling or heat recovery,
- the need to register in the CRO,
- investment cost.

This, in turn, made it possible to evaluate the previously described systems giving one measurable comparative factor for each solution (Table 2). The individual properties evaluation of each system consisted in assigning the "+"

sign, recognized as advantageous for the investor, and the "-" sign, if the given property was considered disadvantageous. Then, summing and determining the overall assessment of each cooling system was made. For simplicity it was assumed that the weight of each criterion is the same.

Table 2 Detailed evaluation of cooling systems

Specific features	Variant 1	Variant 2	Variant 3	Variant 4
1. There is no consumption of coolant	-	+	+	+
2. Once treated cooling medium does not cause deposit scale in pipes and heat exchangers, maintaining the flow efficiency at the same level, through to which the heat reception does not change over time	-	+	+	+
3. Cooling medium is not contaminated	-	+	+	+
4. The oil is cooled with a cooling medium at ambient temperature	-	-	+	+
5. The mould forms are cooled with an water solution of glycol at the same temperature	-	-	-	+
6. Temperature adjustment of the cooling fed medium into the mould form can be done by throttling the flow or by means of a thermostat	+	+	+	+
7. The system requires two circuits: thermally insulated and none-insulated,	+	+	-	+
8. Possibility of energy-saving winter operation using free-cooling or heat recovery	-	-	+	+
9. The need to register in the CRO	+	-	-	+
10. Investment cost	+	-	-	-
Evaluation results:	**-2**	**0**	**+2**	**+8**

Source: (Bernacki, 2018)

BASIC ELEMENTS OF THE INJECTION MOULDING COOLING SYSTEM

Technical and environmental parameters

Next actions in defined as optimal cooling system design process (system with portable chillers and drycooler with adiabatic system) require determining the operating conditions (environmental) for the adopted production plant.

The location of the injection moulding cooling installation will have a significant impact on the optimal configuration of such system. Determining in which climate zone the production plant will be located will an influence on the assumed minimum and maximum atmospheric air temperatures has at different times of the year (minimum winter temperature and maximum summer temperature). For example Poland – Kuyavian-Pomeranian region is the second climate zone, where temperatures are assumed: for winter -18ºC, and for summer +32ºC.

Due to the location of this type of installation in the industrial area, restrictions related to noise levels in particular regarding external devices such as the cooler may be ignore.

Characteristics of the production raw material

Subsequent steps related to the design of the cooling system is to analyse two closely related elements of the production process. The first is the type of plastic processed (shaped) by injection moulding and the second is the injection moulding machine itself which requires adequate cooling to ensure product quality and process continuity.

One of the many raw materials used in the production of injection method, and requiring cooling is i.e. poly (methyl methacrylate) (PMMA), also known as acrylic glass or organic glass. It is a thermoplastic material with exceptional transparency, resistance to UV radiation and mechanical damage (scratches) used among others for car headlights.

Characteristics of injection moulding machines

Based on the authors' own experience and in cooperation with manufacturers of industrial injection systems, the following parameters related to the cooling process were defined:

- cooling power demand related to heat supply to the mould through moulded material N_{kp}:

$$N_{kp} = \frac{GE \cdot X \cdot cp \cdot T}{860} \text{ [kW]} \quad (1)$$

where:

GE – capacity of plastic flow through injection moulding machine [kg/h],

c_p – specific heat [J/kg·K],

T – difference between plasticizing temperature and mould temperature [K],

X – safety factor,

- demand for cooling power N_{kp2}, related to the work of the hot ducts installed in the tool:

$$N_{kp2} = 0{,}65 \cdot NHK \text{ [kW]} \quad (2)$$

where:

NHK – power of hot ducts [kW].

The sum of those two elements gives the total cooling power demand N_k for the injection moulding form:

$$N_k = N_{kp} + N_{kp2} \text{ [kW]} \quad (3)$$

The demand for cooling power associated with maintaining hydraulic oil in the proper temperature regime N_{ol}:

$$N_{ol} = 0.4 \cdot N_o + 0.4 \cdot 18.5 \text{ [kW]} \quad (4)$$

where:

N_o – power of hydraulic pump (drive pump) [kW].

It should be noted that the first two tasks presented by formulas (1) and (2) will be executed in a system with a heat carrier up to +15ºC in portable chillers, while the third process presented by formula (4) will be associated with a medium up to +30ºC in drycooler. This analysis of this case concerns the system of one injection moulding machine. The optimal mould temperature for PMMA have to be determined every time in technological process for type of PMMA and type of manufactured element (Milewski, 2009).

Selection and characteristics of the individual refrigeration unit

The initial selection of a portable chiller can be made on the basis of calculated demand for total cooling power N_k, with the temperature of the medium leaving the chiller equal to +15ºC. The system should be supplemented with a properly selected refrigeration automation and a control system based on a microprocessor controller. An advanced management algorithm striving to work as energy-efficient as possible in combination with a by-pass valve, which under favourable conditions completely by-passes the refrigerant system means that for outside temperatures below + 10ºC the expected cooling capacity is achieved without switching on the compressor. Such action brings measurable financial benefits, and also extends the life of the compressor. Additional to earlier assumptions, to select components that would eliminate the need to register devices in the CRO database, the selected refrigeration unit should contain as less as possible amount of refrigerant. Preferably, if the ratio of mass of a "freon" in the unit and its GWP does not exceed 5000 kg in carbon dioxide equivalent is met.

Determination of the total capacity of the drycooler

Considering the chosen optimal configuration of the system with the portable chillers to ensure the right mould temperature and drycooler to maintain the right oil temperature, it should not be forgotten that the plate condensers of individual refrigerators are cooled with the same coolant as the oil. This makes it necessary to take into account the performance of the external drycooler not the cooling power of these devices but the heat gains from the associated condensers. To perform this analysis it is necessary to recall the technical parameters of the pre-selected bench cooler and the refrigeration compressor used in it together with the working refrigerant. Only this approach will allow determining the amount of heat energy to be collected from the condenser micro chillers, as well as from oil which then must be discharged through the coolant into the environment.

Determination of the efficiency of the external drycooler should guarantee, at an outside temperature of +35ºC, obtaining a temperature of the medium supplying the system (leaving the cooler) equal to +30ºC. Such a parameter is not possible to achieve for a "dry" cooler, therefore devices with an additional sprinkler system that effectively reduces the air temperature at the entrance to the cooler (operation based on a wet thermometer) should be taken into account for the selection (Milewski, 2009).

Selection of optimal coolant and refrigerant

In refrigeration systems, various liquids such as water, ethanol, methanol, ethylene and propylene glycols as well as brines (calcium chloride and sodium chloride) have been used as coolant over the years. Among these substances, brines are highly aggressive and quickly lead to corrosion of pipelines. Alcohols are characterized by high specific heat, less aggressiveness and viscosity, however they are flammable and quite expensive. From many years in similar types of systems water solutions of ethylene or propylene glycol dominate in the use. Initially the more advantageous parameters are propylene glycol solution, it has higher specific heat, is non-toxic, but it is necessary to notice: a much higher kinematic viscosity, which largely translates into the electrical power consumption of the pumps, also smaller coefficient of thermal expansion and the higher boiling point are not without significance. The price difference is also important, because ethylene glycol can be up to 30% cheaper than its propylene equivalent (Bonca et al., 2004).

To select the optimal refrigerant that to use in portable chillers, several aspects should be considered, in particular:

- negative boiling point value at ambient conditions,
- total chemical stability at any temperature in the system,
- chemical inertness towards all materials used in the system,
- non-flammability,
- non-toxic,
- non-explosive,
- large volumetric cooling capacity, in order to reduce the volume flow of the medium circulating in the system, and thus the size of the compressor and the entire installation,
- relatively low GWP parameter, so that the given refrigerant component in the device does not force the need to register in the COR system,
- favourable price and availability of refrigerant.

The parameters of the three most popular refrigerants are presented in (Ullrich, 1999). Taking into account the parameters of these refrigerants and their combinations of evaporation heat, critical pressure and dynamic viscosity of the liquid and relatively low GWP (1624), it can be assumed with such criteria formulated that the refrigerant R407C as optimal for use in portable chillers.

Selection of central drycooler

The choice of central drycooler (central fan cooler) should be made taking into account the indicated climatic zone with its maximum air temperature, the accepted coolant and the expected temperature of this medium at +30ºC at the outlet of the heat exchanger. Because of the fact that the air more and more often reaches the temperature higher than +30°C in our climate zone it makes impossible to achieve in this condition the expected temperature + 30°C at the outlet of "dry" cooler. It is necessary to use a hybrid device, where in the temperature peak periods the drycooler is supported by a system of additional sprinklers on the air inlet side of the cooler. For choosing a drycooler important is:

- total power demand,
- required temperature difference between the inlet and outlet of coolant at 5K (from + 35°C to + 30°C).

Example of such drycooler is shown on Figure 2.

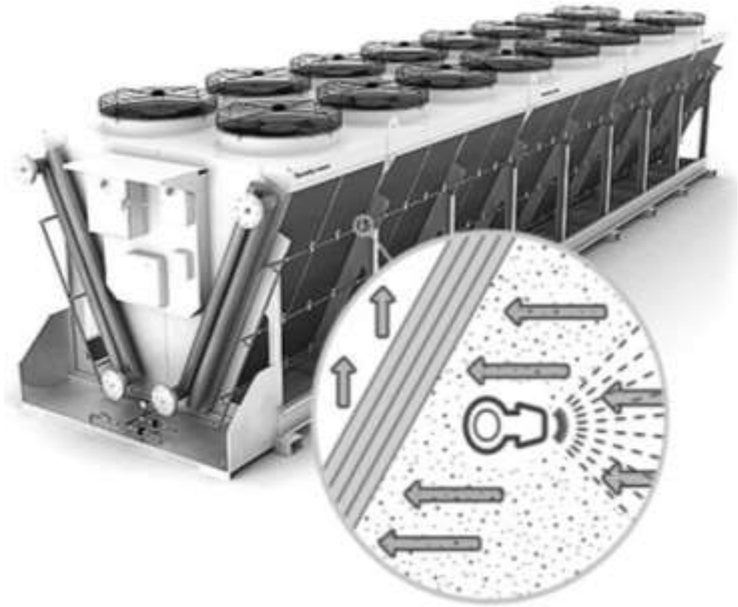

Fig. 2 Example of adiabatic cooling system equipped with special high-pressure water nozzles

Source: (ThermoKey, 2018)

Selection of glycol circulation pump

In the selecting process of a main circulation pump, a number of parameters should be considered (Bernacki 2018):

- capacity determined in the selection of drycooler,
- coolant,
- coolant working temperature,
- total head to cover pressure drops in pipelines and on condensers of portable chillers and coolers,
- power supply.

The selection of a circulation pump can be made by using dedicated computer programs from various manufacturers i.e. Wilo Select 4 [www.wilo-select.com]. Considering the fact that circulating pumps in technological systems work for almost the whole year, when choosing the optimal solution it should be taken into account not only the technical and price parameters associated with the purchase but the total cost of many years intensive use/operation. A tool helpful in this type of analysis is the Life-cycle cost analysis (LCCA) method, which objectively allows verification of the total cost of the system from the moment of purchase, through installation, to operation related mainly to the consumption of electricity. According to the guidelines of this method, individual long-term costs are statistically distributed according to the following proportion for pump and compressor presented at (Fig. 3).

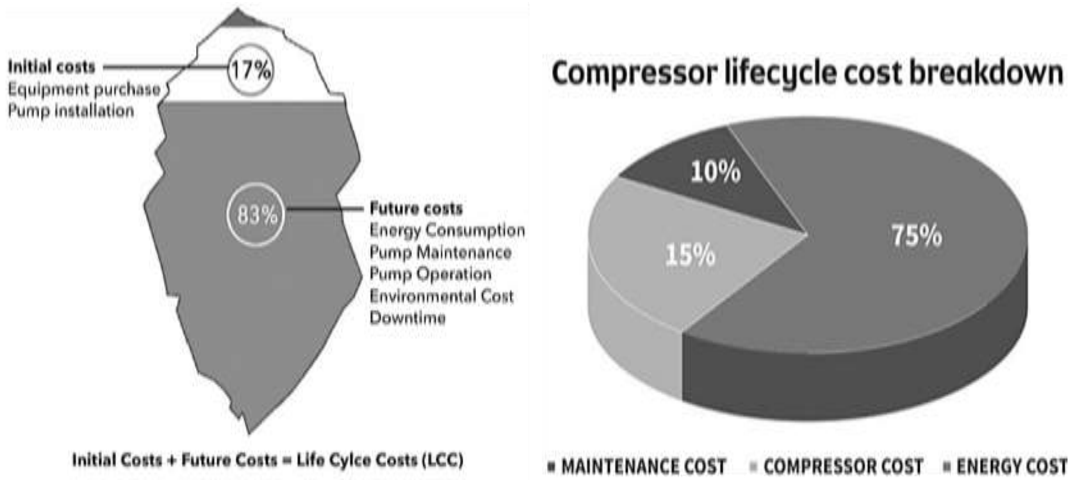

Fig. 3 Example of life cycle costs estimation for pump and compressor – proportions between investment and operation/maintenance costs of devices
Source: (Varadaraj, 2015)

For safety reasons, in terms of ensuring the continuity of the production process it is recommended to adopt the system of two pumps installed in parallel, where one of them performs the function of the main device and the other is switched on in the event of the failure (renovation) of the first.

SUMMARY

The growing popularity and the newer and more demanding use of plastic elements will make manufacturers to analyse the parameters that have a real impact on the quality and cost of producing the new product. The advantages of this type of manufacturing plant, apart from maintaining production continuity and its repeatability, will be the lowest possible process costs and high flexibility directly related to the possibility of simultaneous production of various products with significantly different technological parameters, as well as the ability to change injection equipment in a very short time to perform other tasks.
In this work a review of the most popular solutions related to the cooling systems of injection machines has been made. Both technical and economic aspects were presented. The optimal cooling system of hydraulic oil and injection moulds was determined using portable chillers cooperating with a central -liquid fan cooler equipped with a sprinkler system. This configuration with two temperature systems matched to the heat reception from many individual devices, means that the installation always works with the highest possible efficiency which is further enhanced by switching to "free cooling" mode at an outside temperature below + 10ºC.
An important criterion in the process of optimal design of the cooling system for plastic injection moulding machines is environmental protection. Such a hardware configuration that meets current and foreseen legal restrictions in the field of environmental protection in the near future. On the one hand this approach confirms the awareness of environmental protection and the impact of this type of installation on the environment. And on the other hand makes the

owner (operator) of such installation avoid complicated and expensive procedures related to the registration of equipment and mandatory inspections. At the same time the diffuse of refrigeration system (with low refrigerant charge) ensures greater reliability as well as flexibility in adjusting and maintaining temperature settings for a given specific injection moulding machine.

REFERENCES

Bonca, Z., Butrymowicz, D., Hajduk, T., Targański, W. (2004). Nowe czynniki chłodnicze i nośniki ciepła. Własności cieplne, chemiczne i użytkowe. Gdańsk: IPPU MASTA.

Milewski, P. (2009). Modernizacja systemu chłodzenia wtryskarek linii technologicznej przetwórstwa tworzyw sztucznych – część I. Technika chłodnicza i klimatyzacyjna, No. 8, pp. 286-291.

Milewski, P. (2009). Modernizacja systemu chłodzenia wtryskarek linii technologicznej przetwórstwa tworzyw sztucznych – część II. Technika chłodnicza i klimatyzacyjna, No 10, pp. 368-370.

Ullrich, H. J. (1998.) Technika chłodnicza. Tom II. Gdańsk: IPPU MASTA.

Bernacki, M. (2018). Projekt wstępny systemu chłodzenia z wentylatorową chłodnicą cieczy z systemem zraszania w chłodzeniu wtryskarek w przemyśle tworzyw sztucznych. MSc. Gdynia Maritime University.

Varadaraj, A.J. (2015). Energy Efficiency in Compressors. [online] Available at: https://www.mtwmag.com/energy-efficiency-compressors [Accessed 20 May. 2020].

Thermokey, (2018). Adiabatic systems. [online] Available at:www.thermokey.it/highlights/adiabatic-systems [Accessed 20 May. 2020].

Wilo, (2020). Wilo-Select 4 Online. [online] Available at: https://www.wilo-select.com/ApplRange.aspx [Accessed 20 May. 2020].

Regulation no 517/2014 of the European Parliament and of the Council, on fluorinated greenhouse gases and repealing Regulation (EC) No 842/2006.

Abstract: The paper presents and describes cooling systems mainly used in industrial plants specialized in production based on injection moulding machines. Each solution is rated taking into account investment costs, technical complexity, exploitation costs and system flexibility in general. With regard to dynamically changing law regulations linked to refrigeration installations, mainly F-Gases Act, during optimal system selection new restrictions were respected. This approach ensures long- term exploitation without additional complications. The paper contains characteristics of cooled facility, i.e. production plastic plant using injection moulding machines, presents specifics for this type of application where two extremely different cooling processes are placed in parallel. One task is heat collection from injection moulds to ensure short production time and produced details recurrence, the second is keeping hydraulic oil temperature between temperature limits – this process ensures proper oil viscosity and prevents its premature wear.

Keywords: cooling system, injection moulding, dry-cooling