Program Solution for Regulation and Monitoring of Evaporator Section in Individual Quick-Freezing Process

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***Abstract* - In this paper a program solution for control and monitoring of evaporator section in cooling tunnel is proposed. Control strategy for freezing process is designed to work according to temperature probes used for measurement of temperature of frozen goods. Defrost control is designed to work with active probes used for ice thickness measurement thus providing more efficient defrosting of pipeline section in evaporator. Monitoring of certain values of significance is maintained by using pressure observation in condenser circuit and temperature observation expanded to room/tunnel temperature along with probes used in control (goods' temperature). Also, significant actuator states are also monitored: evaporator fan speed and defrosting heater switching state.**

Keywords - Dynamic defrost control, Evaporator control, Individual quick freezing

I. Introduction

Individual quick-freezing process (IQF) is a dynamic cooling process that takes place in cooling tunnels and is used for freezing and storage of perishable foodstuff in food processing industry such as fish and meat.

A time-maintained control of such freezing process was introduced in [1] and [2] and which included the use of time blocks in LADDER program solution, as opposed to standard simple cooling process which implement mostly one cycle of cooling and optional defrost [3]. This control strategy uses heuristic approach by observing room temperature as indirect indicator on how the goods are being refrigerated and how the icing on the evaporator section is being defrosted. Since it is mainly time-controlled, a strategy defined in [1] is also limited to one cycle of goods' preparation after which a storage of frozen goods must take place in another cold room, thus making the manipulation of goods more complex. This manipulation's time limit is described as follows [1]:

$$T_p = \sum_{i=1}^{n} \left(T_{pr,i} + T_{r,i} + T_{pd,i} + T_{d,i}\right) \qquad (1)$$

where:

- $T_{r,i}$ – refrigeration period,
- $T_{d,i}$ – defrost period,
- $T_{pr,i}$ – pause period before refrigeration,
- $T_{pd,i}$ – pause period before defrosting.

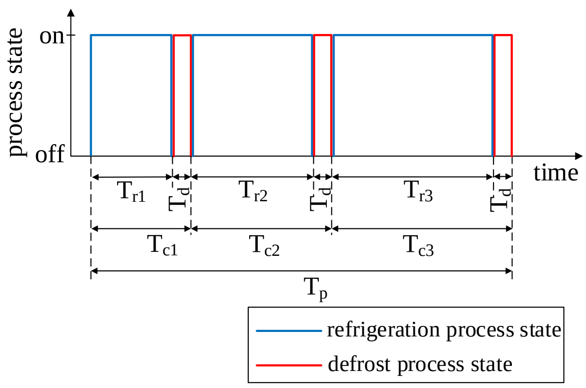

Fig 1. Time flow diagram of a three-cycle IQF process with manipulation time limit [1]

In this paper a novel control strategy is proposed for individual quick-freezing process, with regards to optimal control of defrosting heaters and regulation of cooling process with much more accurate measurement with several additional features such as room temperature and condenser pressure monitoring.

II. Control Strategy for IQF Process and Storage of Goods in Cooling Tunnel

A. *Cooling process with evaporator defrosting*

A cooling effect is obtained in a cold room (in this example a cooling tunnel) by use of refrigerant and various elements of a refrigeration system such as compressor, condenser, and evaporator. In this process a refrigerant is pressurized at different pressure levels in these elements. Heat is absorbed from cold room through evaporator and transported to condenser where it is being released. To reinforce this cooling effect fans on evaporator and condenser are mounted for circulation of air in the environment [4].

Since the icing on the pipeline of the evaporator can be a problem in environments below 0°C, defrosting heaters are mounted in its body with sole purpose to melt the ice and secure the effective circulation of air.

Control of switching of evaporator heaters in a complex cooling process can be demanding to implement, since in dynamic freezing processes the moisture release is very non-linear. Thus, a non-standard control approach by means of ice-thickness monitoring is implemented and tested on a cooling tunnel.

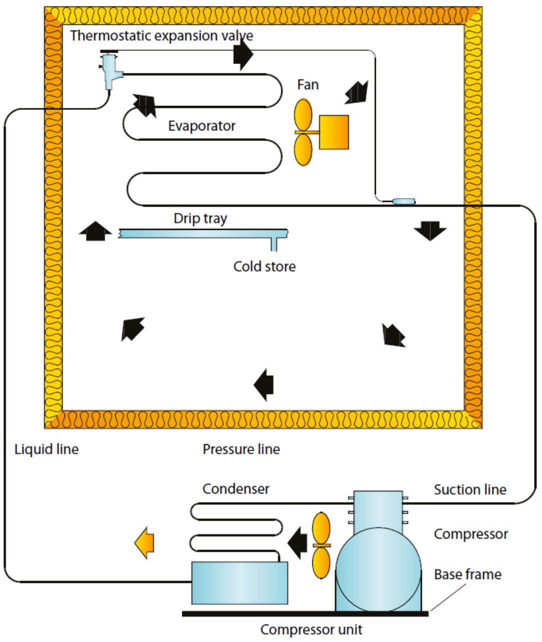

Fig 2. Refrigeration process – principle [3]

B. *Direct measurement used for regulation*

Several improvements are being introduced in this control strategy regarding control that is described in [1], most importantly a use of aseptic and hygienic temperature probe *iTherm TM412* (Endress+Hauser) with 4-20 mA integrated transmitter for direct measurement of goods' temperature and defrost sensor *HBDF-MK2* (HB Products) for dynamic defrost control.

Use of these sensors ensures more dynamic control of cooling/defrost cycles, with program solution being much more efficient, since there is no need to implement timing blocks. With these products cooling tunnel can be more efficient and can be also used as a cold room storage once the IQF process finishes.

C. *Control and monitoring equipment selection*

Siemens S7-1500 modular PLC is used as a primary regulation device. Modules used for implementation, programing and testing are:

- CPU module *6AG1516-3AN01-2AB0*,
- AI module *6ES7531-7KF00-0AB0*,
- DIO module *6ES7523-1BL00-0AA0*.

Also, SINAMICS AC drives are used for regulation of fans' speed according to refrigerant condensing pressure and these devices are connected via PROFINET communication with the CPU module. Condensing pressure is thus connected to analog input of AC drives and this information, along with switching/alarm states of condenser fans, is forwarded via PROFINET to the CPU.

HMI device used for monitoring and reference input is Siemens's touch panel, type *TP700 Comfort* and is connected to PLC via PROFINET for easy user control and observation of measured signals in a controlled system.

A pressure probe is indirectly used for monitoring of condenser's pressure (Danfoss *DST P110, 0-30bar).*

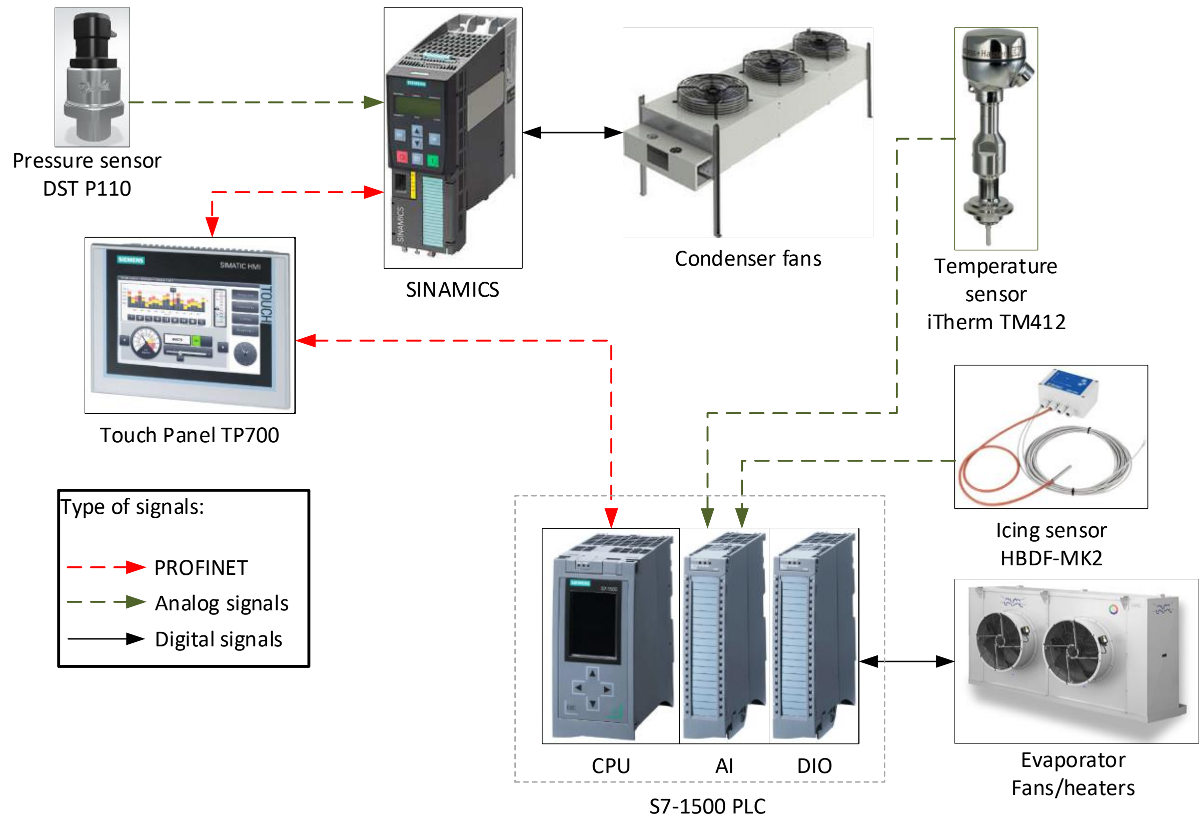

Fig 3. Block schematics of a control system and refrigeration system's elements

III. PROGRAM SOLUTION FOR CONTROL

A. *PLC workflow and addresses*

TIA portal package was used for development of program solution for control and monitoring of a cooling tunnel. For control of a cooling process two temperature sensors are being used, and temperature reference is obtained by:

$$T_{ref} = \frac{T_{probe1} + T_{probe2}}{2} \quad (2)$$

These sensors measure temperature of goods in cooling tunnel during refrigeration and room temperature. With two sensors a more accurate measurement is being performed. This reference is used for switching the cooling elements on by use of user set temperature and a dead zone (usually set to 2°C). Tested system uses reference of -35°C with dead zone of +2°C, making the dead zone in between -35°C and -33°C, for better assurance of quality of goods [5, 6].

Icing sensor is used as a measuring element for evaporator defrost control, and thickness of the ice is set from 0 mm to size of the fin spacing in evaporator's body (tested system uses evaporators with 12mm fin spacing). Regulation reference is set to 10% with dead zone of 20% of the fin spacing range. Measurement scaling is:

$$\langle 0 \div fin\ space \rangle \xrightarrow{AI} \langle 4 \div 20mA \rangle \xrightarrow{PLC} \langle 0 \div 100\% \rangle \quad (3)$$

Condenser fans are being switched on after a cooling state is set to ON and are being regulated by use of AC drives with pressure as a reference for speed control of fans.

Since the icing of evaporator is primarily used as a reference for switching between states of refrigeration and defrost, a control strategy developed in observed system uses icing measurement as primary instrument in the alternation of cooling and defrosting cycles. These dynamics that are being introduced in control strategy make the whole system work in optimal state with regards to effectiveness of cooling and energy consumption.

Workflow diagram is shown on fig. 4. On this diagram one cycle of PLC is observed. First cycle starts with setting the process in the state ON by user. Process is being maintained in this state until end user turns it off via user interface on HMI device.

Addresses used for observed states and measurements are shown in table I. These signals are being processed in PLC throughout one cycle of PLC's operation and forwarded to HMI device for user observation and control.

TABLE I. – SIGNAL ADDRESSES

Signal	*Type*	*Communication*	*Data type*	*Address*
Cooling state ON	Digital	DIO module	Bool	Q0.0
Defrost state ON	Digital	DIO module	Bool	Q0.1
Ice thickness	Analog	AI module	Real	IW4
Temperature 1	Analog	AI module	Real	IW6
Temperature 2	Analog	AI module	Real	IW8
Evaporator fan state	Digital	DIO module	Bool	I1.0
Evaporator heater state	Digital	DIO module	Bool	I1.1
Evaporator fan alarm	Digital	DIO module	Bool	I1.2
Evaporator heater alarm	Digital	DIO module	Bool	I1.3
Condenser/Compressor fan state	Digital	PROFINET	Bool	PI80.0
Condenser fan alarm	Digital	PROFINET	Bool	PI80.1
Condenser ON	Analog	PROFINET	Real	PQ60.0
Condenser pressure	Analog	PROFINET	Real	PID84
Condenser fan speed	Digital	PROFINET	Real	PID88

Digital outputs are used for switching the evaporator fans and electromagnetic valve (Q0.0) and for switching defrost heaters (Q0.1). These signals are mutually exclusive. As a feedback information for these actuators, digital inputs I1.0 and I1.2 are used for evaporator fans while I1.1 and I.3 are used for evaporator heaters.

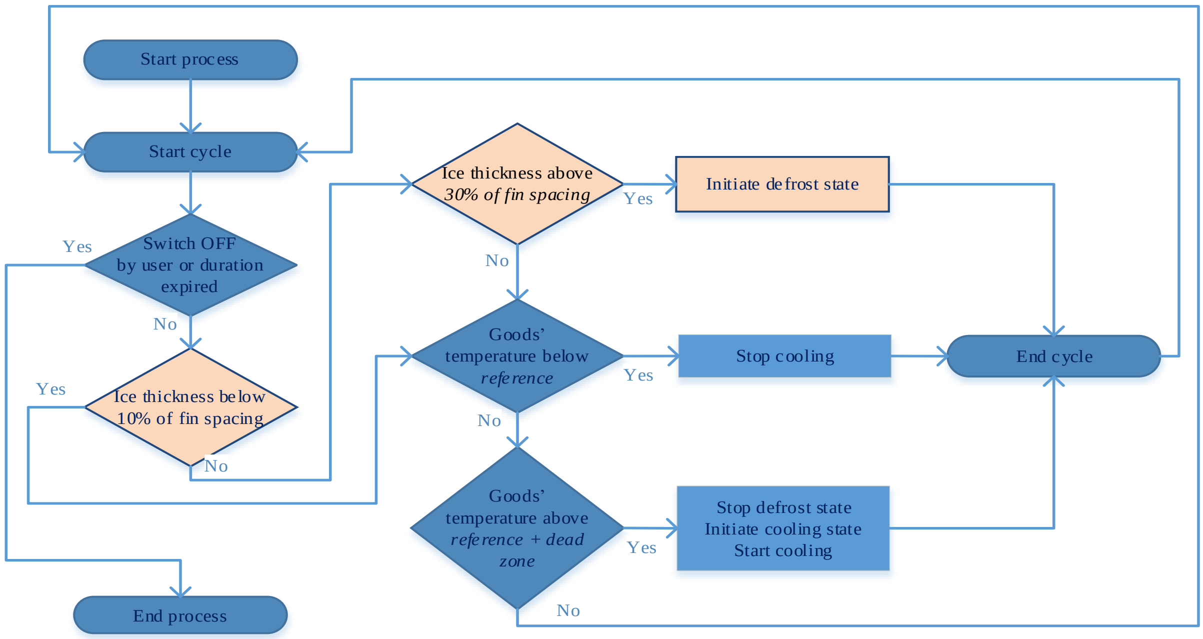

Fig 4. Work flow diagram of one cycle in control process of defrost and cooling states of evaporator

B. *HMI user interface*

User interface consists of four different screens which implement the possibility of parameter change, monitoring of significant refrigeration values and observation of process finishing. These screens are navigated through according to logic presented on fig. 5.

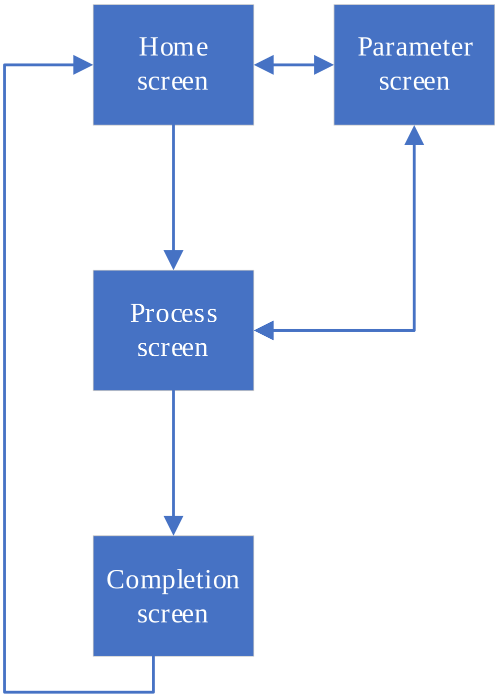

Fig 5. Refrigeration process – principle [3]

Home screen is a starting screen for user, and it contains possibilities to navigate to parameter screen or start the pre-parameterized quick-freezing process, as is shown on fig. 6.

Parameter screen is designed to set the cooling temperature reference and relative thickness of icing according to evaporator fin spacing, as is shown on fig. 7. These parameter settings are to be set according to limits: maximum value of reference temperature is -5°C and ice thickness is 90% of absolute fin spacing. These maximum values are defined for the greater flexibility of user's choice of frozen goods and defrost control according to ice thickness. Also, an IQF process duration can be defined.

Once the parameters are set and the process is initiated by the user, a process screen appear in which a user can observe significant process values such as goods' temperature, room temperature, evaporator temperature, refrigerant pressure in suction pipeline and relative ice thickness on evaporator. Parameters can be changed also by navigating to parameter screen, and process can be also stopped by the user. Process screen is shown on fig. 8.

Last screen that can be obtained after a freezing process is done is a completion screen, shown on fig. 10. After a process completes after defined duration (set on parameter screen) a single message appears, noting the user that a quick-freezing process is complete and that the further manipulation of goods may be performed.

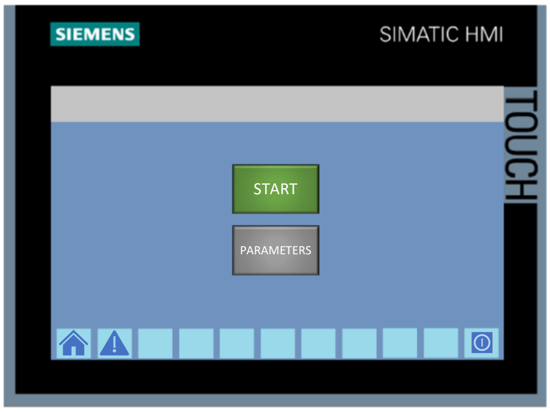

Fig 6. HMI - home screen

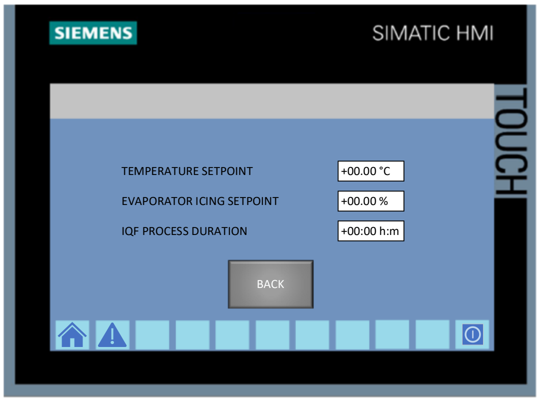

Fig 7. HMI – parameter screen

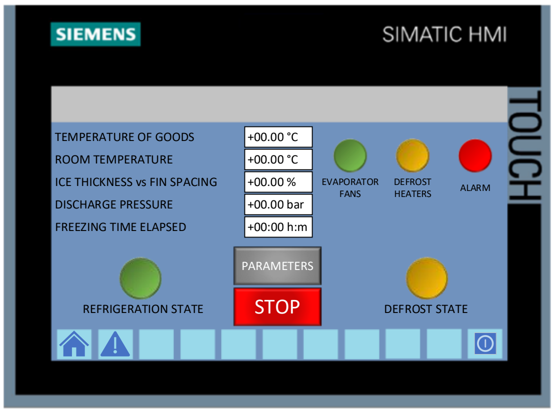

Fig 8. HMI – process screen

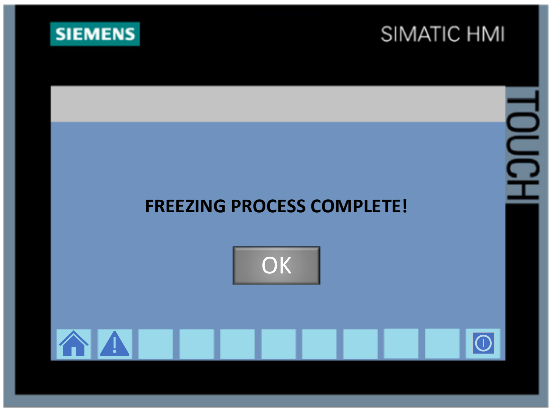

Fig 9. HMI – completion screen

IV. Defrost Control Evaluation – Testing Results

Observations for the testing case were made for a cooling tunnel used for applying IQF process in freezing a fresh fish. Nominal carrying capacity of a tested cooling tunnel is 15 tons of goods in a single intake.

Cooling system of a tested tunnel has the same principle of operation as described in [1], with the main changes being made to defrost regulation of the evaporator, used by means of icing thickness dead-zone control. Also, changes in the principle of condenser fan regulation have been made. Condenser fans are operated by the SINAMICS devices, thus giving a finer approach to pressure and condensing temperature regulation.

Three test cases were observed, and these vary according to carrying capacity of a cooling tunnel: 70%, 100% and 120% of a nominal capacity (15 tons of fresh fish). Temperature median was obtained as mean value of room and goods' temperature readings and was used for evaporator fan switching state control by means of a dead zone regulation. Icing thickness readings are used for defrosting heater switching state control.

While defrost mode is on, heaters are always on. When appropriate icing thickness is achieved, heaters are switched off, cooling state control takes place, and evaporator fans are switched on according to temperature median.

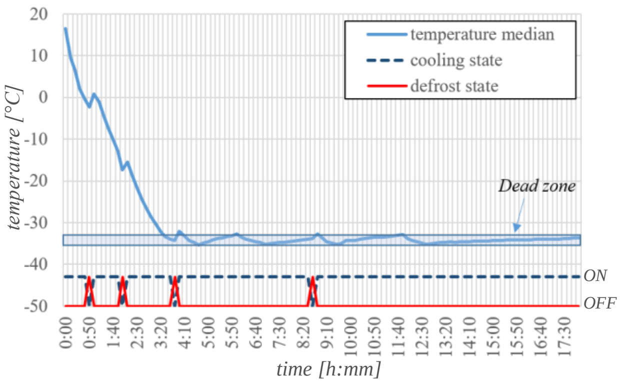

Fig 10. Temperature median graph of an IQF process in a tested cooling tunnel – 70% of nominal carrying capacity

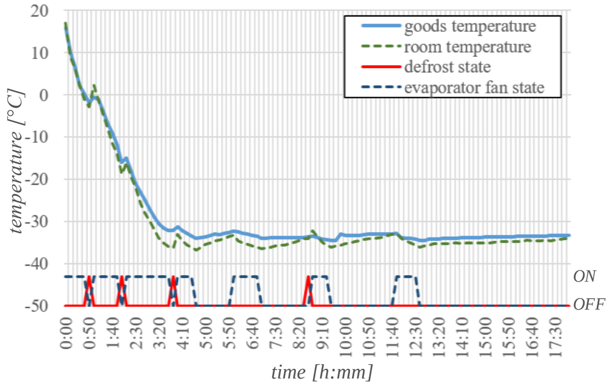

Fig 11. Room and goods' temperature graph of an IQF process in a tested cooling tunnel – 70% of nominal carrying capacity

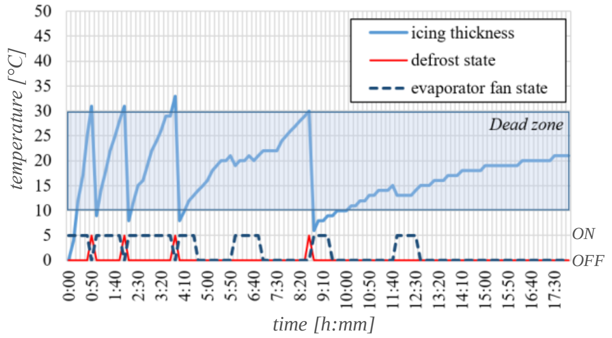

Fig 12. Icing thickness graph of an IQF process in a tested cooling tunnel – 70% of nominal carrying capacity

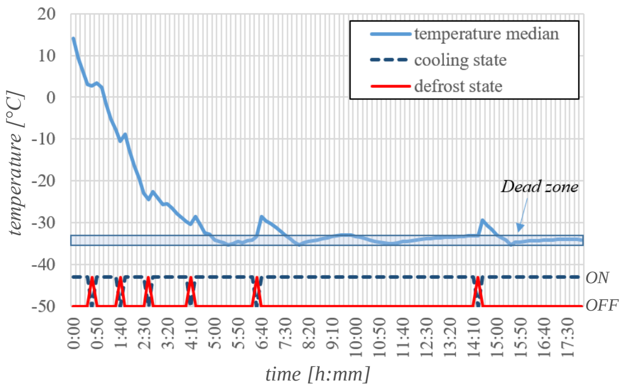

Fig 13. Temperature median graph of an IQF process in a tested cooling tunnel – 100% of nominal carrying capacity

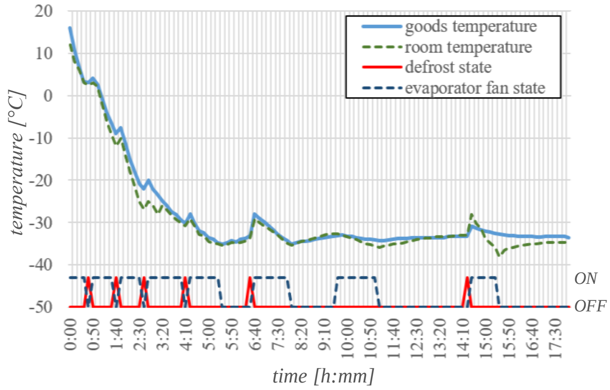

Fig 14. Room and goods' temperature graph of an IQF process in a tested cooling tunnel – 100% of nominal carrying capacity

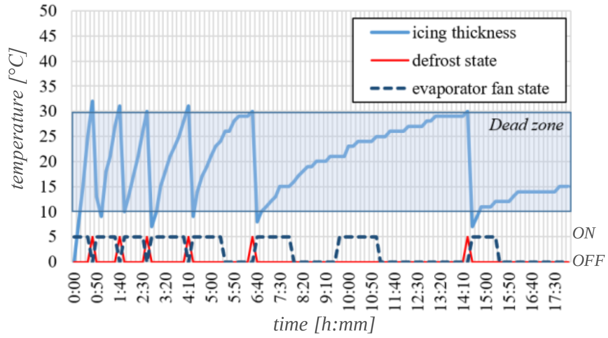

Fig 15. Icing thickness graph of an IQF process in a tested cooling tunnel – 100% of nominal carrying capacity

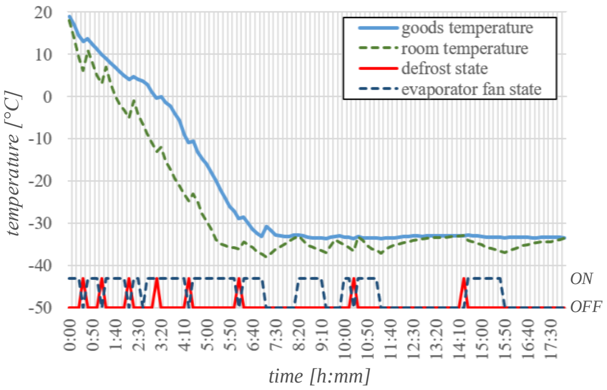

Fig 16. Temperature median graph of an IQF process in a tested cooling tunnel – 100% of nominal carrying capacity

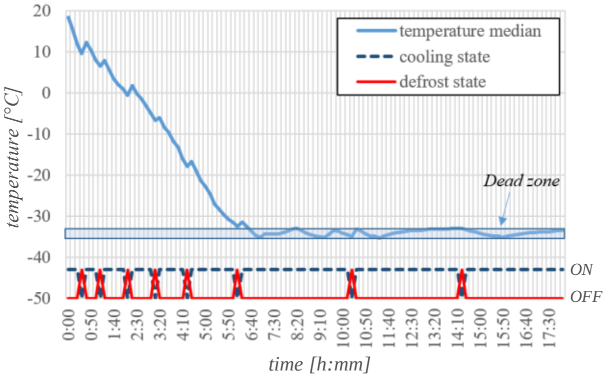

Fig 17. Room and goods' temperature graph of an IQF process in a tested cooling tunnel – 100% of nominal carrying capacity

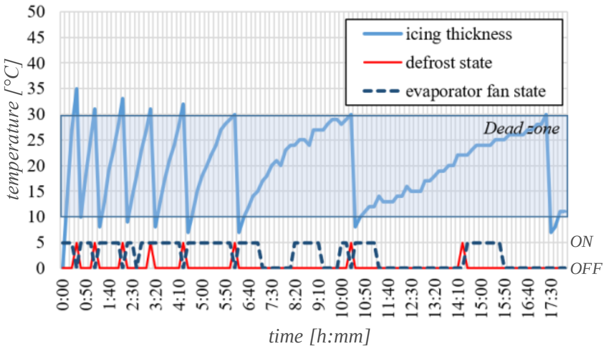

Fig 18. Icing thickness graph of an IQF process in a tested cooling tunnel – 100% of nominal carrying capacity

Results of testing the icing thickness control strategy for 15-ton fresh fish cooling tunnel show that in each of the test cases a referenced median temperature is obtained in the first half of the freezing process duration cycle. Number of defrost cycle increases according to tonnage of the load being frozen. More accurate measurements were made by two probes: one used for direct measurement and placed in goods and one used for room temperature monitoring. A deviation gap between these two measurements was slightly more significant in a case of a slightly overloaded tunnel, but in general, it can be concluded that these gaps are of acceptable value for effective freezing of goods.

When compared to control strategy presented in previous research tests [1] for the same tunnel, control strategy via icing thickness outperforms time-maintained control strategy for the cases of 100% and 120% carrying capacity of a tested tunnel. As a consequence lesser and variable defrost duration times prove to be a better solution for overall refrigeration system performance than the previously implemented control strategy. Also, an ice-thickness control strategy is not that much dependent on an amount of goods being frozen, as much as is the strategy described in [1] and [2], which is a main problem in quick achieving a desired temperature and a quality of frozen goods in an overloaded tunnel.

V. CONCLUSION

Dynamic control of defrost duration and switching was implemented with the idea of upgrading an existing refrigeration process control. The main reason lies in the modernization process of an existing refrigeration system with the purpose of more flexible use of a cooling tunnel. With the more dynamic control of evaporator section (mainly, a defrosting process), an end-user can utilize the tunnel for freezing various amounts and types of goods, not only the ones that it was initially designed for. Also, a flexibility is manifested through lesser time that a tunnel performs a freezing to a certain goods' temperature point.

An HMI interface was made as simple as possible, since only temperature and ice thickness variables are parameters of interest to the evaporator control strategy process.

Although the process control with static defrosts and fixed number of defrost cycles is a more cheap and sufficiently effective control strategy for monitoring and regulation of an IGF process in cooling tunnels, a described dynamic control in this paper seriously outperforms the former method. This evaporator control method optimizes the use of heaters for defrost through ice thickness monitoring, while also switching evaporator fans in a more effective manner during a cooling state. This effectiveness is manifested through a better circulation of a cold air in a tunnel during cooling, since there is a strict control of an ice volume on the body of an evaporator.

With the more effective use of all the actuating devices in an evaporator section, and with the SINAMICS on a condenser section, an electric power consumption is more effective, thus giving a possibility of an investment return.

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