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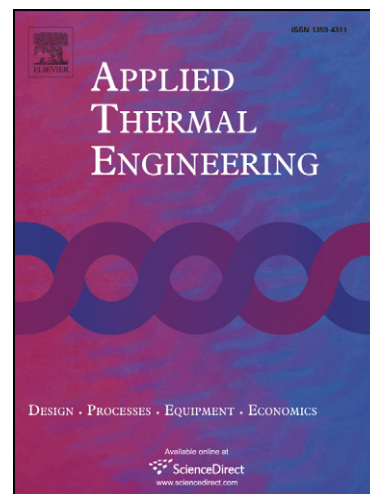
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Two kinds of gravitational ejector refrigerator stimulation

abbreviated title: **Stimulation of an ejector refrigerator**

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Abstract

Temperatures and levels of refrigerant in the heat exchangers of a gravitational ejector refrigerator make a combined system of numerous mutual couplings. It has some significant properties of self-regulation. There are three kinds of reaction on the self-regulation system of the refrigerator: thermal-type when it is stimulated by changing the temperature of exchangers surrounding, ejector-type stimulated by changing the ejector's geometry or refrigerant kind, volume-type stimulated by changing the amount of refrigerant. The predicting of a specific reaction of a system balance is difficult but it may be obtained by a mathematical model and calculating experiments.

Keywords

ejector system

gravitational refrigerator

hermetic device

stimulation

Symbols

A – the cross-section area of heat exchanger, m^2

F - the area of heat transfer, m^2

g - gravitational acceleration, $m\ s^{-2}$

h - height, m ,

m - mass flow ratio, $kg\ s^{-1}$,

p - pressure, Pa ,

Q – heat flux, W ,

t - temperature $^{\circ}C$,

v - specific volume, $m^3\ kg^{-1}$,

V - volume, m^3

COP - coefficient of performance (refrigerating cycle)

subscripts and superscripts

c – condenser

e - evaporator

ej – ejector

en – energy

ext - external (temperature)

g - steam generator

liq - liquid

ref – refrigerant

vap - vapour

Main text

1. Introduction

The ejector refrigerators have been known in engineering since the beginning of the 20th century thanks to the works of LeBlanc and Parsons [1]. At first, water was used as a refrigerant, later the refrigerants known from compressor refrigerators were used [2]. In the works concerning ejectors Alexis, Katsanis [3] used alcohols, Selvaraju, Mani [4], Pridasawas, Lundqvist [5,6], Boumaraf, Lallemand [7] hydrocarbons.

There are few publications concerning the gravitational ejector refrigerators. In a publication Nguyen, Riffat, Doherty [8] described a refrigerator in a form of a 5-meter high tower with water as a refrigerant. The refrigerator used a one-way valves at the inlet of a steam generator and an evaporator. Additionally an expansion valve was fixed. Ling [9] described an gravitational ejector refrigerator in a vertical arrangement with water as a refrigerant and a pump supply of a steam generator. In some research (Srisastra, Aphornratana, Sriveerakul [10,11], Huang, Hu, Lee [12]) double tanks or valves with a cyclic steam generator feeding system have been used. The applied systems of thermal pumping allowed to decrease the refrigerators height to some significant extent. Technical literature does not provide descriptions of the gravitational refrigerators working without pumps, one-way valves, tanks and cyclic feeding system.

The unique research concerning this area has been published [13] by the author of this publication.

2. A conception of a gravitational refrigerator

In a pump version of the ejector refrigerator (Fig.1a) a disposition of devices in a vertical axis is optional. Heat exchangers may be placed on different levels towards one another. The flows of liquid refrigerant are forced by the pump work, which, as the only one part, contains movable parts. A structure of the gravitational ejector refrigerator (Fig.1b) does not allow to put the exchangers in any way, because of the pressures which balance at the bottom pipe of the refrigerator. The lowest pressure in the refrigerator installation is obtained in the evaporator. It causes the inflow of liquid to the highest installation level. The highest pressure is obtained in a steam generator, which forces the lowest liquid level. The specific of the work of the gravitational system is isentropic expansion of the refrigerant into a liquid pipes and evaporator volume. This effect should theoretically slightly increase the efficiency of the refrigerator but practically is insignificant.

The ejector cycle allows to build a hermetic gravitational refrigerators, like, much better known absorptive cycle with inert gas [14]. The hermetic refrigerators are regarded as exceptionally durable and reliable because they do not contain movable parts. Moreover, they are quiet. The size of gravitational refrigerators and especially their height depend on the applied refrigerant and levels of temperature in particular parts of the device.

3. The usefulness of the refrigerant for the gravitational refrigerator

Low pressure refrigerants are used the most effectively for work in the gravitational refrigerator. Low pressure and high density of saturated liquid allow to construct the refrigerators of small height. The specific parameter which proves the usefulness of the refrigerant is the value of liquid height changed due to saturation temperature. The liquid level is pushing down (according to the gravitational forces), as a result of the saturated steam pressure in a specific temperature which has been shown in the Fig. 2. A negative derivative value means that the level of refrigerant decreases with the increase of temperature:

$$\frac{dh}{dt} = -\frac{dp(t)}{dt} \cdot \frac{v_{liq}(t) - v_{vap}(t)}{g} \approx -\frac{dp(t)}{dt} \cdot \frac{v_{liq}(t)}{g} \text{ [mK}^{-1}\text{]} \quad (1)$$

Large value of the derivative (1) proves usefulness of the refrigerant (for ex. ammonia). Small value of the derivative (water, alcohols, heavier hydrocarbons) means that the refrigerator works at small differences of pressures between a steam generator and an evaporator causing the small height of device. It is worth noticing that even for the best refrigerant the derivative value (1) strongly depends on the temperature. In the range of temperatures 0÷100°C the derivative value changes from 10 to 100 times for most refrigerants. In the ejector device the highest temperature level occurs in the steam generator and the value of eq. (1) is the highest there as well. The large value of derivative means that the changes of the temperature of refrigerant are going to cause the changes of liquid level in the heat exchanger. Cross-section, heat transfer area and heat transfer coefficient are going to change with the change of filling height. The correct work of the refrigerator depends on the proper liquid level in all three heat

exchangers. The phenomena of the changing levels may be advantageous or disadvantageous for the work of refrigerator - it needs analyzing.

4. Self-regulation of the steam generator

The strongest dependence (1) of the height of liquid on the saturation temperature occurs the steam generator. The coefficient values dh/dt obtained for water as a refrigerant at the temperature $+80^{\circ}\text{C}$ amount to -0.2 mK^{-1} . The increase of temperature t_{g_ext} of the generator surrounding causes the increase of temperature t_g of boiling refrigerant. Steam pressure p_g pushes down the h_g liquid level, decreasing area F_g of heat transfer. Total liquid push-out from the generator is not possible as it would stop a steam generation. It makes a back coupling causes the liquid level goes up again (Fig.1). The described phenomenon may be advantageous. The heat transfer in the generator is self-regulating: while increasing the surrounding temperature the heat transfer is limited, while decreasing the surrounding temperature the heat transfer is intensified.

5. Condenser's self-regulation

The boiling phenomenon occurs below liquid surface, the condensation phenomenon occurs above liquid surface. In the condenser the heat transfer area concerns an area filled with steam as shown in the Fig.3. During temperature increase of condenser's surrounding t_{c_ext} the temperature t_c inside the condenser, pressure p_c of condensed steam increases as well and liquid level h_c is pushed down increasing simultaneously the F_c area of the heat exchange. Inversely, a drop of condensation temperature

increases liquid level and decreases the area of the heat transfer with the condenser's surrounding. The described phenomenon is beneficial, the heat transfer in the condenser has self-regulation: while increasing the surrounding temperature the heat transfer process is intensified and while decreasing the surrounding temperature the heat exchange is limited. The obtained coefficient (1) values dh/dt for water as a refrigerant at temperature $+35^{\circ}\text{C}$ amount to -0.033 mK^{-1} .

6. Evaporator's self-regulation

In the evaporator the lowest temperatures of refrigerating cycle occur and contrary to the generator the dh/dt values are insignificant here. For water as a refrigerant at temperature $+15^{\circ}\text{C}$ this coefficient amounts to -0.012 mK^{-1} . Increase of temperature t_{e_ext} of the evaporator surrounding causes the increase of t_e temperature of evaporating refrigerant. The pressure p_e of vapour pushes down the liquid level h_e , decreasing area F_e of the heat transfer (Fig.2). The described phenomenon is not advantageous, the surface of heat transfer in the evaporator diminishes when the surrounding temperature increasing. The total push-out of the liquid from the evaporator is not possible as it would stop the evaporation. It makes the back coupling and the liquid level goes back to the appropriate level.

The phenomena of the evaporator's self-regulation should be analyzed together with the flow ejector characteristic. The evaporation limitation decreases also the stream of vapour sucked up by the ejector. In reaction to this the ejector decreases pressure in a suction area and thanks to this, increases h_e level in the evaporator, enlarges the heat transfer area F_e and intensifies evaporation. Inversely, the increase of evaporation

pressure pushes down the liquid level decreasing the heat transfer with simultaneous increase of the stream of steam sucked up from the evaporator.

7. Model of self-regulation for the gravitational ejector refrigerator

A significant phenomenon taking place in the described device is constant amount of the refrigerant. The refrigerant pushed out from one of the heat exchangers is forced into the other two exchangers. This phenomenon has serious consequences especially for the liquid pushed out from the steam generator because the derivative value dh/dt is the highest for the temperatures in the steam generator. It is difficult to predict whether the liquid pushed out from the steam generator flows in the most part to the evaporator or to the condenser. This phenomenon demands the analyse of plenty of phenomena taking place in gravitational ejector refrigerator.

In the previous publication [13] the calculating model for the phenomena taking place in the gravitational ejector refrigerator has been presented. In the model assumptions six independent variables have been taken into account. For each of three heat exchangers there are: temperature and the height of filling of refrigerant liquid. Mathematical calculating model is based on six balance equations:

- the equation of balance of refrigerant cycle energy
 - the equation of the balance of flows in ejector
 - the equation of balance of amount of refrigerant
 - the equation of balance of pressures between generator and evaporator
 - the equation of balance of pressures between generator and condenser
 - the equation of balance of pressure between condenser and evaporator

The way of formulating the model equations is the best given by the matrix form of the eq. (2), where the matrix contains coefficients $a_0 \div a_{35}$, which are strongly non-linearly independent from the variables $t_g, t_c, t_e, h_g, h_c, h_e$.

$$\begin{array}{l}
 \text{1.eq. of energy balance} \\
 \text{2.eq. of ejector's flow balance} \\
 \text{3.eq. of refrigerant's volume balance} \\
 \text{4.eq. of generator - evaporator balance} \\
 \text{5.eq. of generator - condenser balance} \\
 \text{6.eq. of condenser - evaporator balance}
 \end{array}
 \begin{bmatrix}
 a_0 & \dots & a_7 \\
 \dots & & \dots \\
 \dots & & \dots \\
 \dots & & \dots \\
 \dots & & \dots \\
 a_{30} & \dots & a_{35}
 \end{bmatrix}
 \times
 \begin{bmatrix}
 t_g \\
 t_c \\
 t_e \\
 h_g \\
 h_c \\
 h_e
 \end{bmatrix}
 =
 \begin{bmatrix}
 w_{en} \\
 w_{ej} \\
 w_{ref} \\
 0 \\
 0 \\
 0
 \end{bmatrix}
 \quad (2)$$

Fig.4 presents a scheme of couplings occurring in the gravitational ejector refrigerator. Numbered denotations on the scheme are in accordance with the way of the balance equations numeration (2). The eq. marked as 1 defines energetic relations of three heat exchangers of the refrigerator. Eq. 2 defines flow relations in ejector and refrigerant's properties. Eq. 3 defines relations between the liquid pushed out from the one of exchangers and forced in to two others. The eq. 4,5,6 define the balance between the liquid height in the generator, evaporator and condenser. The whole refrigerator's system is full of mutual couplings and predicting the refrigerant's reactions is difficult. The right side of the eq. (2) contains three non-zero values : w_{en}, w_{ej}, w_{ref} . Those values define three basic ways of influencing on parameters inside refrigerator: thermal-type – stimulated by changing the temperature around the exchangers, ejector-type – by changing the ejector's geometry and volume-type – by changing the refrigerant's amount. The specific characteristic for each of these reaction types are as following:

- Thermal-type:

Expression w_{en} is linear function of surrounding temperature t_{g_ext} , t_{c_ext} , t_{e_ext} for all three exchangers. Changing the conditions of surrounding the system of refrigerator's coupling is evoked by the value of expression w_{en} . This change may be realized in a continuous way.

- Ejector-type:

Expression w_{ej} is linear function of the ejector characteristic and properties of the refrigerant. The change of ejector's geometry is difficult to realize. The change w_{ej} may also be realized by the change of refrigerant. The refrigerant change may be realized only in a abrupt way, never continuous.

- Volume-type:

Expression w_{ref} is equivalent to total amount of the liquid refrigerant in the installation. If the refrigerator was made of metal and is hermetic than the simple change of the amount of refrigerant is not possible. The problem is more explained in section 9.

8. Calculating experiment with the thermal-type stimulation

The special software for calculations was developed and several calculating experiments have been done. The aim of the experiments was comparison of the model's reaction on changes of temperatures outside the steam generator, condenser and evaporator and comparing the obtained results of temperature changes and liquid levels with the values of derivative dh/dt from the formula (1). The conditions of experiment fulfill previously described way of thermal-type of stimulation on the gravitational ejector refrigerator.

The standard working conditions for the ejector were: the temperature +80°C in steam generator, +35 °C in condenser, +15 °C in evaporator has been used in the calculating experiment with the gravitational ejector refrigerator. The water was used as a refrigerant and allowed in this case to build a gravitational refrigerator. The dimensions of considered device are rather small size (about 5m height similar to [8]) and theoretically reached $COP \approx 0,16$. The results of calculating simulations have been put in the Fig. 5, 6, 7.

In the case of steam generator (Fig.5) a decreasing of liquid level along with temperature increase is visible. The curve of decreasing is inclined less than the derivative value dh/dt for a particular temperature. It may mean that except for self-regulation of the liquid level resulting from pressures inside the generator, the other heat exchangers react here, as well as characteristic of ejector and allocations of the refrigerant.

In the case of condenser (Fig.6) a strongly changeable dependence of the liquid level in the function of temperature changes is visible. A decreasing curve in the centre is inclined inversely than the derivative value dh/dt relation for the given temperature. It may mean that self-regulation of liquid level resulting from a system of pressures inside the condenser is too weak towards to other reactions.

In the case of evaporator (Fig.7) a decrease of liquid level along with an increase of temperature is visible. A decreasing curve is inclined less than the derivative value dh/dt line for a given temperature. It may mean that except for a self-regulation of liquid level resulting from the system of pressures inside the evaporator the other heat exchangers, ejector characteristic and allocations of the refrigerant react in here.

9. Calculating experiment with the volume-type stimulation

According to a patent application [15] it is possible to make a special tank with changeable volume, for instance by using a compensatory metal bellows (Fig.8). Using a tank does not increase a leak of the refrigerant. Changing the tank's value may be a result of external interactions (for ex. a squeeze), and internal ones (for ex. refrigerant's pressure). Generally, an enlarging of the refrigerant's tank causes outlet of refrigerant simultaneously from all three heat exchangers, reduction of a tank causes the increase of these levels. It strongly disturbs a system of balance and a simple defining of a refrigerator's reaction on the change of the refrigerant's amount is not possible. What is possible, however, is doing a calculating experiment in order to test the reaction of a cycle on changes of the amount of the refrigerant in refrigerator's installation.

The conditions of experiment fulfill the previously described way of volume-type stimulation on the gravitational ejector refrigerator. The same parameters as in the previous experiment have been applied to the calculating experiment. The results of calculating simulations have been put in the Fig. 9, 10. The obtained results show that the decrease of refrigerant's amount is associated with temperatures decrease (Fig.9) in all three exchangers of the refrigerator, a reverse process takes place with the increase of refrigerant's amount. The temperature change is the strongest in the case of the evaporator, the weakest in case of the steam generator - it is in accordance with a size of derivatives dh/td in particular exchangers.

In the Fig.10 the dependence of cooling capacity and COP (coefficient of performance) have been shown for the analyzed refrigerator depending on amount of refrigerant. This dependence is strongly changeable and a loss 0.03dm^3 of the refrigerant

causes a four-times decrease of cooling capacity. The cooling capacity achieves a clear maximum for some filling value; a similar dependence shows COP as well, although both maximums occur for different values of refrigerant's filling.

10. Conclusions

1. It is possible to predict the changes of liquid levels as a reaction on the temperature changes of the refrigerant in the heat exchangers of the gravitational refrigerator only for the separated alone heat exchanger. An indicator of these changes is a derivative value dh/dt for the refrigerant's temperature.
2. Three kinds of the reaction on the gravitational refrigerator have been proposed and described:
 - thermal-type - stimulated by the change of temperatures of exchanger's surrounding
 - ejector-type - stimulated by of the change of ejector's geometry or refrigerant change
 - volume-type - stimulated by of the change of the amount of refrigerant.

The method of thermal-type and volume-type do not increase a leak of installation and the changes may take place in a continuous way. The method of ejector-type, by the change of ejector's geometry, is difficult to realize but it may take place in a continuous way. The change of refrigerant's kind may be realized only in a abrupt way.

3. The calculating experiment showed that the temperature change in the steam generator evokes the change of liquid level. This change is definitely weaker than it would result from the derivative value dh/td for the temperature in a steam generator. The temperature change in the evaporator causes the change of liquid level in it. This change is significantly weaker than it would result from the derivative value dh/td for the temperature in the evaporator. The change of temperature in the condenser evokes the change of liquid level but it is inverse to expectations resulting from the derivative values dh/td for the temperature in the condenser (the liquid level increases along with the temperature instead of decreasing).
4. The change of the amount of refrigerant in the refrigerator makes the establishment of a new system of balance parameters. Predicting the reaction of the system on the changes of filling with the refrigerant is difficult. The calculating model allows to check refrigerator's reaction in a simple way.
5. The calculating experiment proved that the decrease of the amount of refrigerant decreases the temperatures in all three refrigerator's exchangers: the strongest in the evaporator, the weakest in the steam generator.
6. The calculating experiment proved that by changing the amount of refrigerant the maximum cooling capacity may be obtained. It appears that with help of the model the optimal amount of refrigerant in the installation may be determined. The cooling capacity achieves maximum with this optimal amount.
7. The calculating experiment proved that by changing the amount of refrigerant the maximum COP value may be obtained. It appears that with help of the model the optimal amount of refrigerant in the installation may be determined. COP achieves maximum with this optimal amount.

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Figure Captions

Fig. 1. Pump and gravitational ejector refrigerator.

Fig. 2. Reaction of refrigerant level in the steam generator and the evaporator on temperature change.

Fig. 3. Reaction of refrigerant level in the condenser on temperature change.

Fig. 4. System of mutual reaction in the gravitational ejector refrigerator

Fig. 5. Changes of liquid level as a reaction on the change of refrigerant temperature in the steam generator.

Fig. 6. Changes of liquid level as a reaction on the change of refrigerant temperature in the condenser.

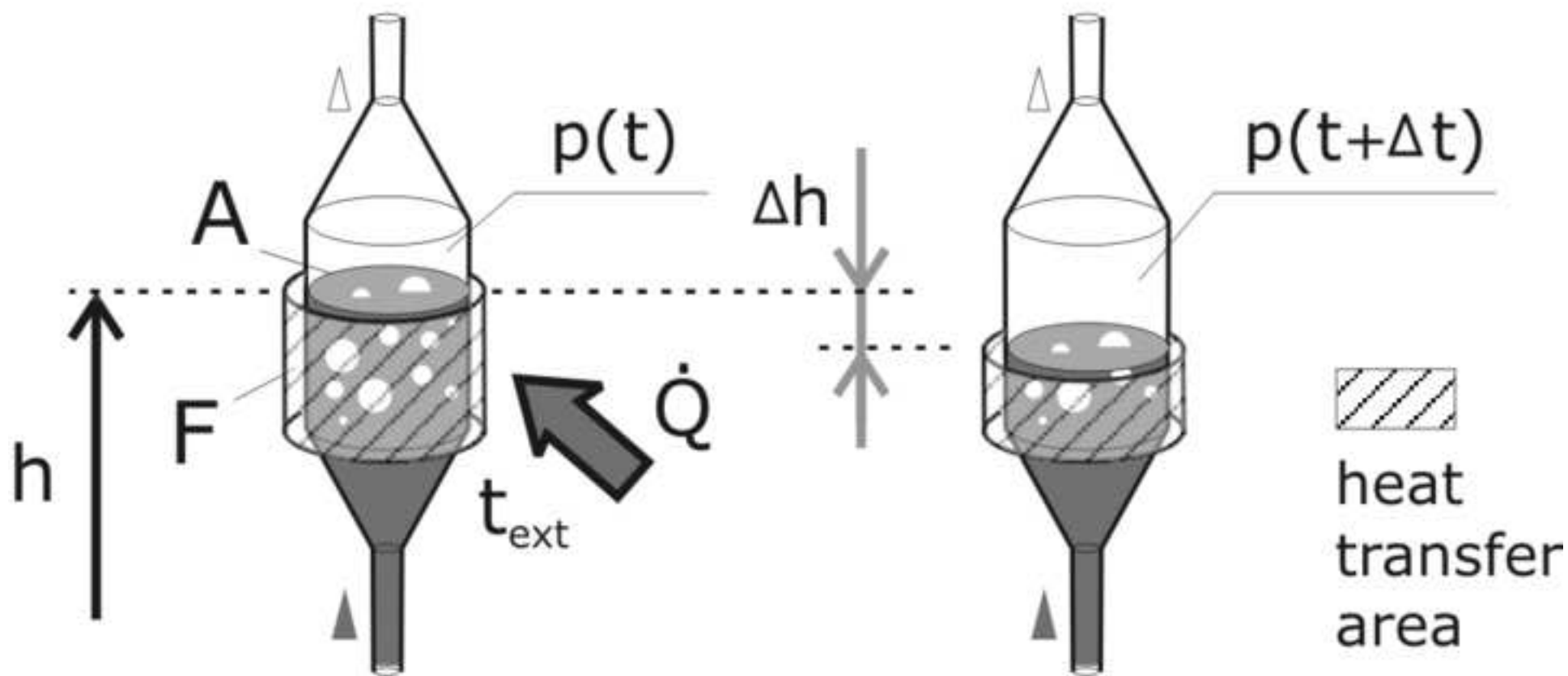
Fig. 7. Changes of liquid level as a reaction on the change of refrigerant temperature in the evaporator.

Fig. 8. Additional tank with changeable volume for liquid refrigerant.

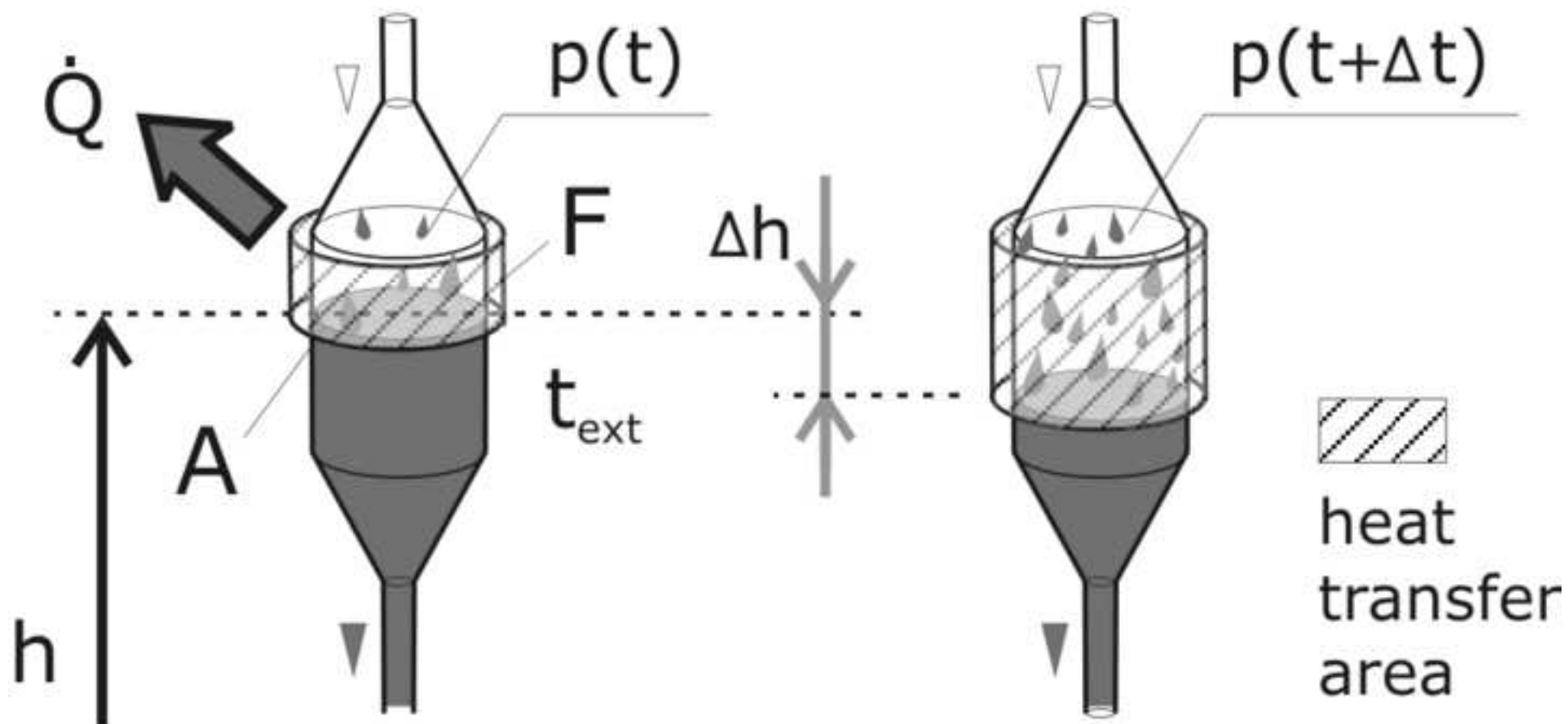
Fig. 9. Changes of temperatures in the exchangers as a reaction on the change of refrigerant's amount.

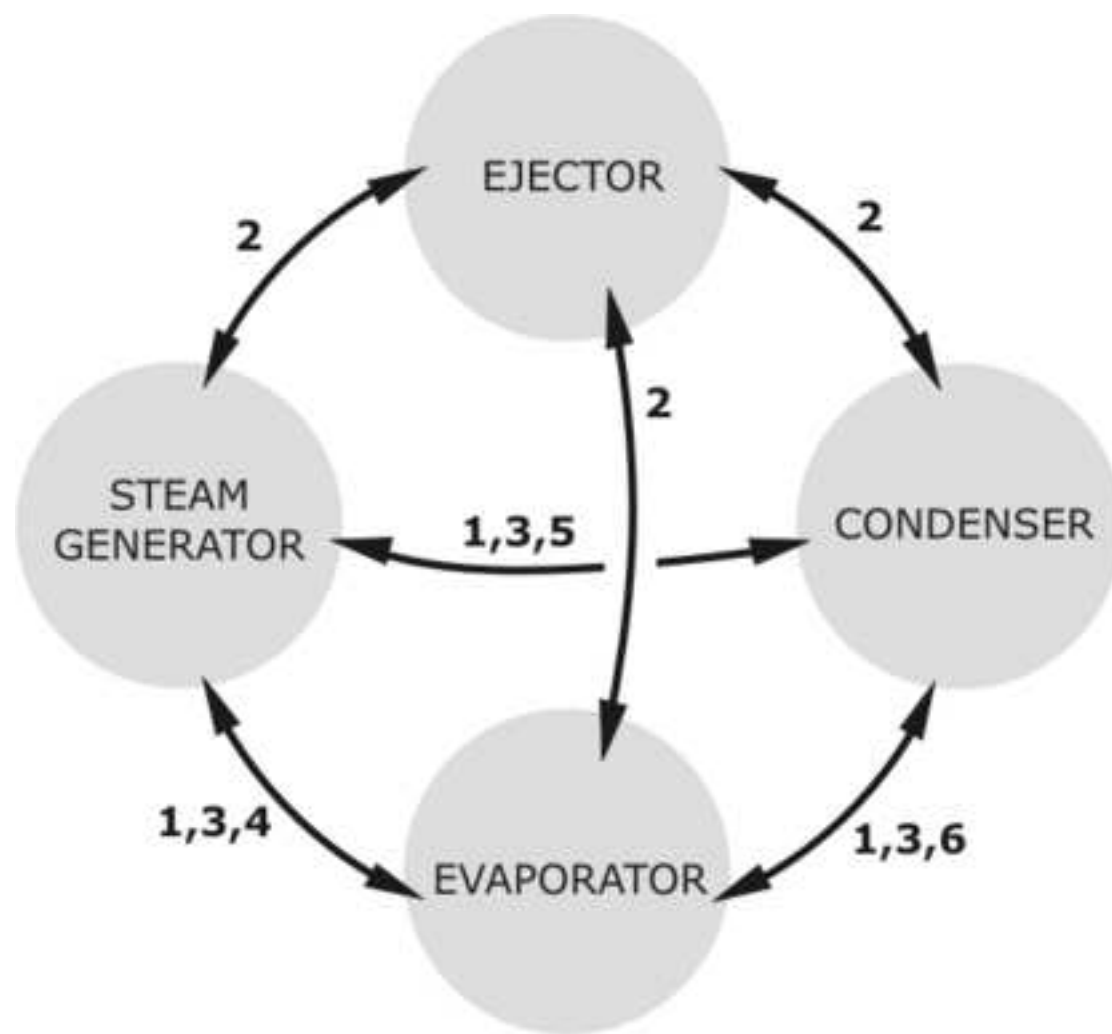
Fig. 10. Changes of a cooling capacity and COP of the refrigerator as a reaction on the change of refrigerant's amount.

STEAM GENERATOR, EVAPORATOR



CONDENSER





1. energy balance equation
2. ejector's flow balance equation
3. refrigerant's volume balance equation
4. generator-evaporator pressures balance equation
5. generator-condenser pressures balance equation
6. condenser-evaporator pressures balance equation

Figure 5

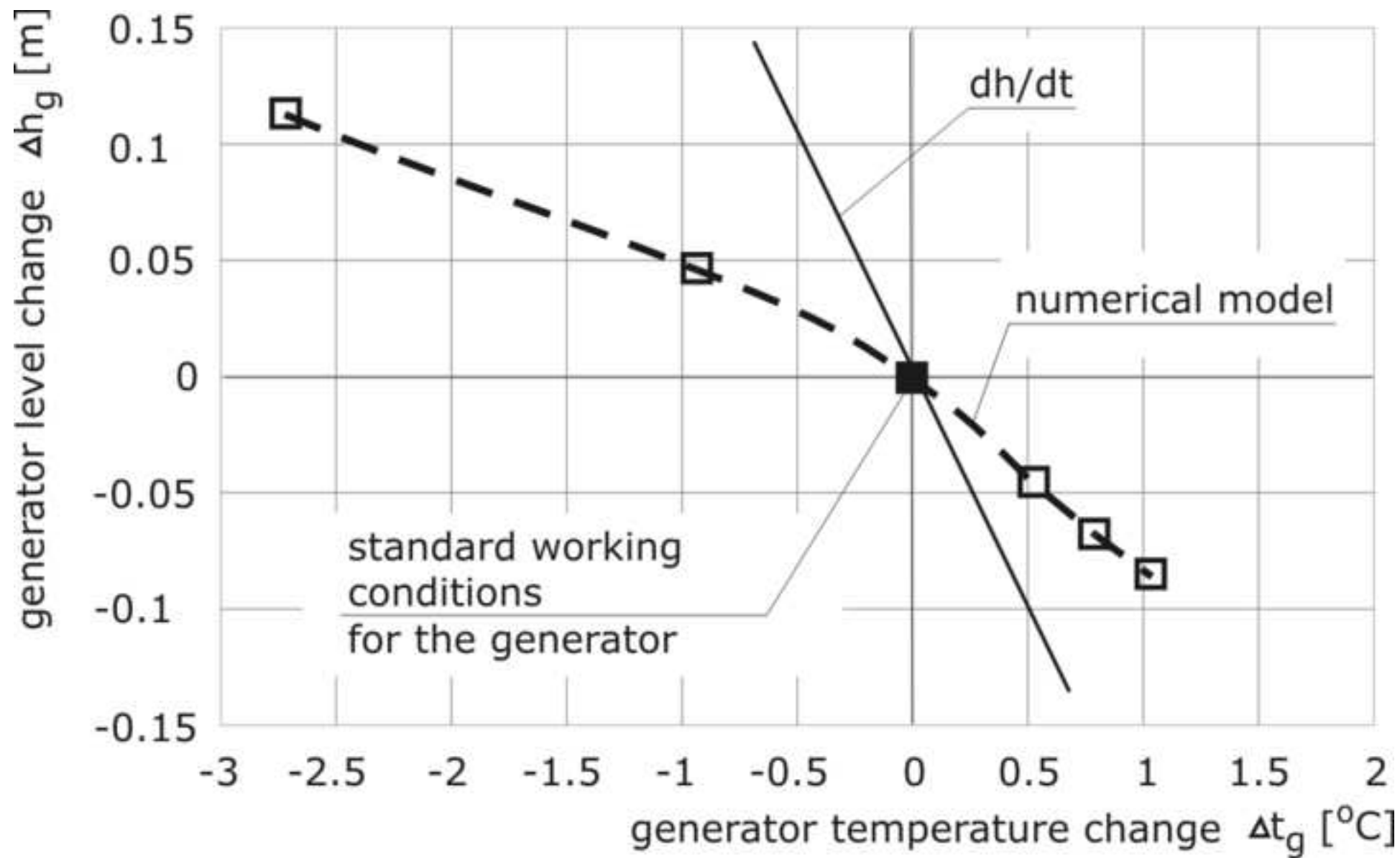


Figure 6

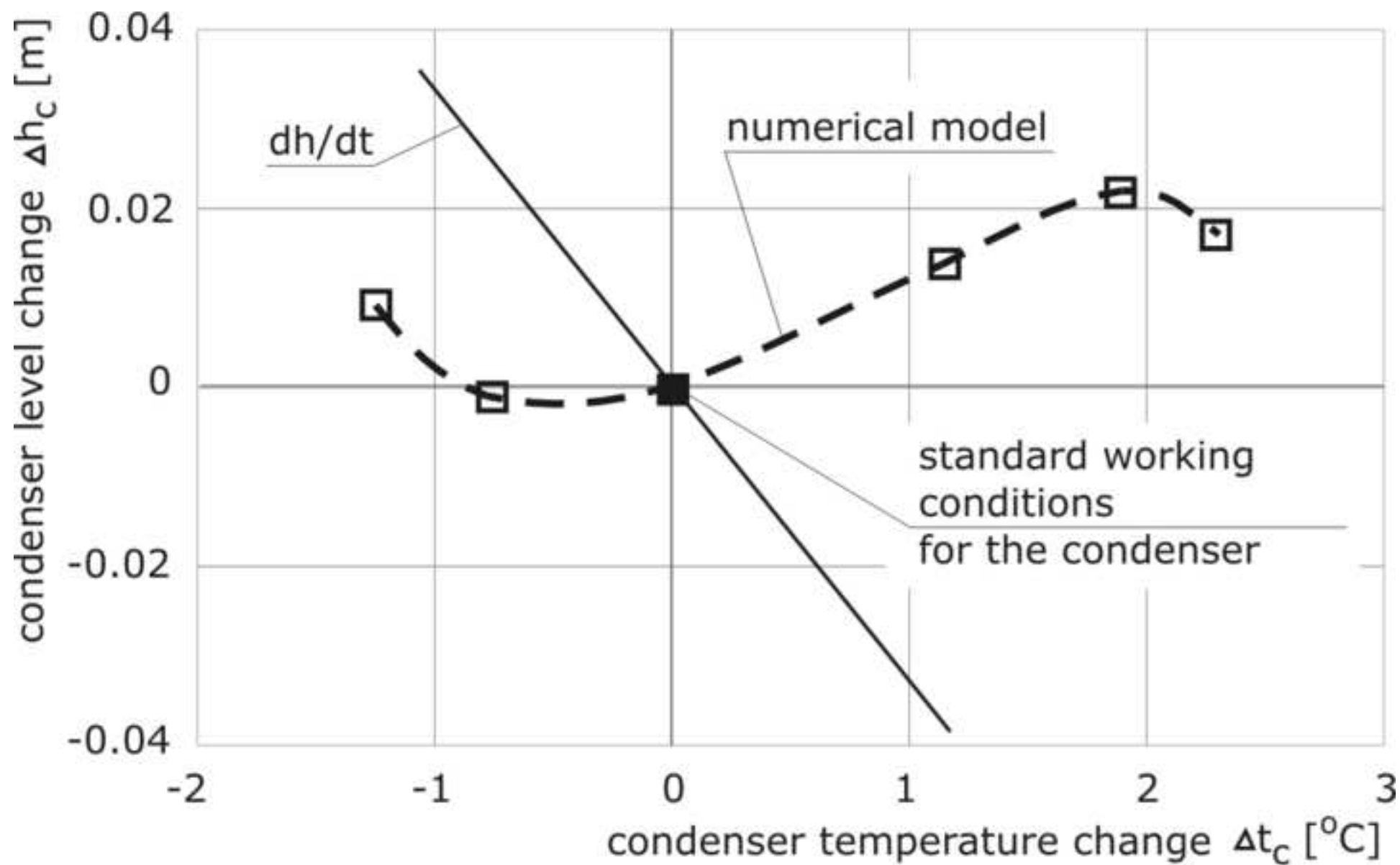


Figure 7

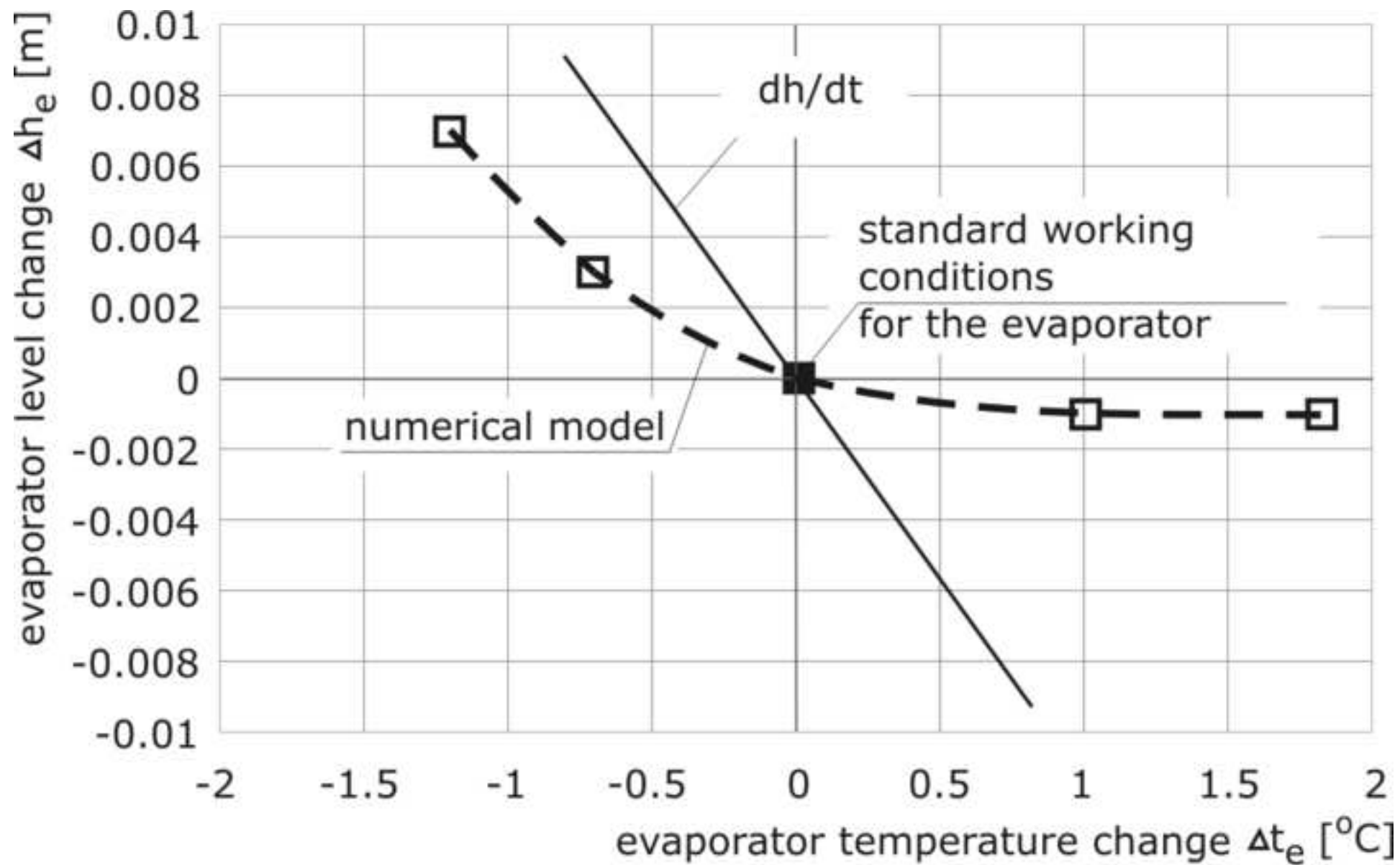


Figure 8

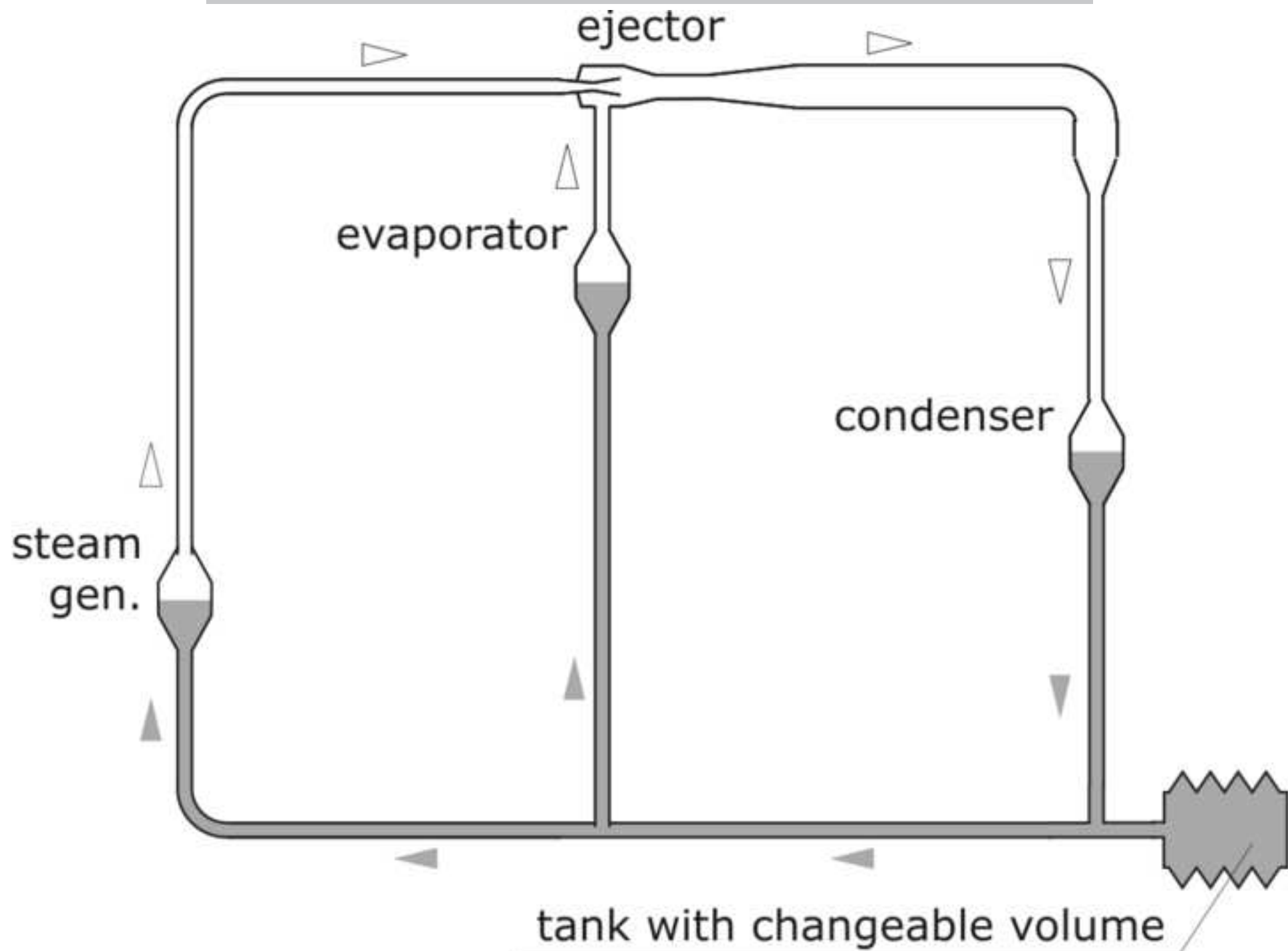


Figure 9

ACCEPTED MANUSCRIPT

