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Céline Petit, Benjamin Siedel, Damien Gloriod, Valérie Sartre, Frédéric Lefèvre, et al.. Adsorption-based antifreeze system for loop heat pipes. Applied Thermal Engineering, 2015, 78 (5), pp.704-711. 10.1016/j.applthermaleng.2014.11.028 . hal-01287008

HAL Id: hal-01287008

<https://hal.science/hal-01287008>

Submitted on 11 Mar 2016

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Manuscript Number:

Title: ADSORPTION-BASED ANTIFREEZE SYSTEM FOR LOOP HEAT PIPES

Article Type: Research Paper

Keywords: loop heat pipe; water; anti-freeze device; adsorbent; storage tank; silica gel

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Abstract: The use of water in loop heat pipes (LHP) is known to be desirable: water is almost freely available; it exhibits high thermal performance and is non-toxic. Nevertheless, water has a major drawback which is its anomalous expansion when cooled down to a negative temperature that is likely to damage the capillary wick of the LHP. To overcome this problem, a storage tank may be coupled to the loop heat pipe. It contains a strong adsorption capacity material designed to adsorb the fluid during shutdown phases of the system and to desorb it during startup phases. A storage tank using the RD-type silica gel as adsorbent material was designed. It is a passive system, which does not require mechanical elements to circulate the fluid and does not degrade the thermal performance of the device, while a secondary auxiliary heating system is required to desorb the fluid. Furthermore, it may be located away from the heat source and it is compact. The simulation results show that the storage tank volume is acceptable and requires moderate energy to desorb the fluid.



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Villeurbanne, 24 July 2014

Editor of Applied Thermal Engineering

Dear Editor,

Please find on the Elsevier server several uploaded files containing a manuscript we wish to publish in Applied Thermal Engineering (1 cover letter, 1 text, 1 highlights, 12 figures).

The article is entitled: "**ADSORPTION-BASED ANTIFREEZE SYSTEM FOR LOOP HEAT PIPES**" and is presented by: **C. Petit, B. Siedel, D. Gloriod, V. Sartre, F. Lefèvre, and J. Bonjour.**

This manuscript is a Research Article presenting a concept of an antifreeze system based on the phenomenon of adsorption that can be associated to a Loop Heat Pipe (LHP) so as to allow the use of water as the working fluid.

I state here that this manuscript is original and has not been published and is not currently submitted elsewhere.

Please feel free to contact me during any step of the revision process.

Best regards,

Prof. Jocelyn BONJOUR



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Highlights (for review)

- A tank containing an adsorbent is associated to a LHP to protect it from freezing
- This storage tank enables the use of water as the working fluid of the LHP
- Several configurations are proposed for this association
- Simulation results show that the storage tank volume is acceptable
- Simulation results show that the power required by the system is moderate

ADSORPTION-BASED ANTIFREEZE SYSTEM FOR LOOP HEAT PIPES

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ABSTRACT

The use of water in loop heat pipes (LHP) is known to be desirable: water is almost freely available; it exhibits high thermal performance and is non-toxic. Nevertheless, water has a major drawback which is its anomalous expansion when cooled down to a negative temperature that is likely to damage the capillary wick of the LHP. To overcome this problem, a storage tank may be coupled to the loop heat pipe. It contains a strong adsorption capacity material designed to adsorb the fluid during shutdown phases of the system and to desorb it during startup phases. A storage tank using the RD-type silica gel as adsorbent material was designed. It is a passive system, which does not require mechanical elements to circulate the fluid and does not degrade the thermal performance of the device, while a secondary auxiliary heating system is required to desorb the fluid. Furthermore, it may be located away from the heat source and it is compact. The simulation results show that the storage tank volume is acceptable and requires moderate energy to desorb the fluid.

Keywords: loop heat pipe, water, anti-freeze device, adsorbent, storage tank, silica gel

NOMENCLATURE

List of symbols

A	cross-section	m^2
c	specific heat capacity	$J.kg^{-1}.K^{-1}$
h	heat transfer coefficient	$W.m^{-2}.K^{-1}$
l	length	m
m	mass	kg
P	pressure	Pa
p	perimeter	m
Q	thermal energy	J
q	adsorption capacity	kg of refrigerant/kg of dry adsorbent
T	temperature	K
V	volume	m^3

Greek letters

λ	thermal conductivity	$W.m^{-1}.K^{-1}$
ρ	density	$kg.m^{-3}$

Subscripts

ads	adsorption
amb	ambient
C	condenser
cc	compensation chamber
cp	connecting pipe
G	vapor grooves
L	liquid line
l	liquid
LHP	inside the LHP
max	maximum
min	minimum
sg	silica gel
V	vapor line
v	vapor
w	water
wi	capillary wick

INTRODUCTION

Loop heat pipes (LHP) are efficient heat transport devices mainly made up of an evaporator containing a porous structure and of a condenser, both elements being connected by separate vapor and liquid flow lines. The passive fluid circulation, induced by the capillary pressure in the porous medium, as well as the use of latent heat of vaporization enable the transport of high amounts of thermal energy, even against an adverse gravity field. These two-phase systems were developed in the 1970's in the Soviet Union and they have already proven their reliability and high performance in numerous spatial applications. They are today candidate for terrestrial applications, such as aeronautic and automotive industries. In the last decade, many investigations were undertaken in order to further develop these systems and to improve them *i.e.* to increase their flexibility, efficiency, reliability and possibility of implementation in existing architectures ([1-4]). For example in [5], a LHP was designed in order to cool electronic components embedded in civil and military avionic equipments. The use of water as working fluid was envisaged in this device because of its numerous advantages: it is almost freely available, it exhibits high thermal performance and it is non-toxic. In this kind of applications, the working fluid is subjected to temperatures between 0 °C and 100 °C. Conversely, when the LHP is at shutdown, the device can be subjected to freezing temperatures. Below 0 °C, water expansion is likely to damage the capillary wick or the liquid line of the LHP.

Various solutions were suggested in the past to overcome the drawbacks related to the water solidification, when it is subjected to temperatures below its solidification temperature. In many engineering objects, an antifreeze mixture is added to water to prevent ice formation below 0 °C. Nevertheless, the use of binary fluids in heat pipe is not suitable because of the serious reduction in their efficiency in such conditions. In order to partially compensate the increase of the liquid volume when it solidifies, the use of suspended nanoparticles was proposed by Sarno and Tantolin [6]. These particles have the ability to bear a certain compression during solidification, thus limiting the overall expansion of the liquid. Nevertheless, it is likely that these particles will not be drained with the vapor. They may rather be stopped in the wick in working conditions, thus degrading the performance of the LHP and limiting their effects to the wick and not the liquid line.

In this paper, a new system using an adsorption material is proposed [7]. Adsorption is the physical process through which molecules of a fluid called adsorbate are fixed onto the surface of a porous solid, called adsorbent. There are two kinds of adsorption processes: physisorption (or physical adsorption) and chemisorption (or chemical adsorption). In the case of physical adsorption which is of interest in the present work, interactions between the adsorbent and the adsorbate of electrostatic nature, mainly due to Van der Waals forces. These interactions are weak and reversible. This is why the adsorbed molecules can be easily desorbed by reducing the pressure or increasing the temperature. As a matter of fact, adsorption is an exothermic process and is favored by low temperatures. Conversely, desorption is an endothermic process and is favored by high temperatures. The principle of adsorption was already used in some applications of heat pipes ([8-9]), in order to enhance the heat transfer intensity in the porous evaporator using a sorbent bed.

We consider a storage tank which contains an adsorbent material and that is connected or embedded in a LHP. At low temperatures, during shutdown phases of the LHP, the adsorbent material has the ability to adsorb significant amounts of water. Removing the vapor from the capillary wick and the liquid line constitutes a method to protect the LHP against freezing. On the contrary, during startup phases, the material adsorption capacity decreases due to the temperature increase. Part of this fluid is thus desorbed and enters the LHP, enabling its effective operation. This device does not require mechanical elements to circulate the fluid since the movements are linked to the sorption phenomena. In addition, the desorption process can help the LHP startup. The aim of the present article is to prove the feasibility of this original system, to design it, to determine its dimensions, its operational temperature and the energy that has to be supplied for its operation.

1. OPERATING PRINCIPLE OF THE ADSORBENT STORAGE TANK

Several solutions are proposed to associate the adsorbent storage tank to a LHP. The first configuration consists in creating a by-pass of the evaporator-reservoir assembly, where the adsorbent storage tank is connected to the LHP by means of a connecting pipe between the liquid and the vapor lines (Figure 1). Three valves and a thermal link between the storage tank and the evaporator are required to enable the operation of the device. In the second configuration, the storage tank is connected with a pipe to the vapor line of the LHP (Figure 2). Such a solution avoids the use

of valves, but it requires an auxiliary heating system to heat up the tank instead of the thermal link mentioned in the first configuration. This system enables placing the tank away from the heat source, where more space is available. Finally, the adsorbent material can be arranged directly within the evaporator-reservoir envelope of the LHP (Figure 3). This latter configuration enables the device to operate fully autonomously, without any valve or auxiliary heating system, but it can be shown that it requires a larger quantity of adsorbent material than with the previous configurations.

In any case, whatever the configuration, the device is used to significantly reduce the amount of working fluid that remains inside the LHP during shutdown phases and thus prevent its deterioration.

1.1. DEVICE WITH VALVES AND A THERMAL LINK (CONFIGURATION #1)

A LHP is mainly composed of the following elements (Figure 1): an evaporator in contact with a heat source, a reservoir for the two phase (liquid-vapor) fluid conventionally named “compensation chamber”, a condenser in contact with a heat sink, the cooling fluid circulating throughout the device, a liquid line and a vapor line. In addition, the present device comprises a storage tank between the liquid and the vapor lines, three valves and a thermal link connecting the storage tank to the evaporator. The thermal link is a highly thermally conductive medium.

In operation, when the LHP transports heat from the evaporator to the condenser, valves 2 and 3 are closed while valve 1 is open, enabling the device to operate identically as a LHP without any antifreeze system. The liquid evaporates in the evaporator, where it is drained by the capillary pressure effect. It is then transported to the condenser where the vapor condenses, and returns to the evaporator. During the LHP shutdown, valves 1 and 3 are closed, while valve 2 is open. At this moment, the heat generated by the exothermic reaction of adsorption is transmitted to the evaporator through the thermal link, which favors the evaporation of the liquid remaining inside the evaporator. The overpressure generated by the evaporation of the fluid as well as the depression in the storage tank due to the adsorption of the fluid make the fluid flow towards the storage tank. When the amount of adsorbed fluid is considered sufficient, valve 2 is closed. Thus, when the LHP does not operate – *i.e.* when it must be protected against freezing if stored in an environment whose temperature is below 0 °C - the storage tank is hydraulically isolated from the other components of the device. When starting the device, valve 2 is closed, while valves 1 and 3 are open. The heat of the heat source is therefore transferred to the tank through the thermal link, which enables the desorption of the adsorbed fluid owing to the temperature increase. The overpressure generated by the fluid desorption and the depression caused by its condensation in the condenser are the driving force for the fluid motion toward the compensation chamber. When the amount of desorbed fluid is sufficient, valve 3 is closed and the system works again as a conventional LHP.

1.2. DEVICE WITH AN AUXILIARY HEATING SYSTEM (CONFIGURATION #2)

In some applications where space is limited, the storage tank cannot be located in the vicinity of the heat source. Another solution is then proposed, where it is linked to the vapor line of the LHP by a connecting pipe (Figure 2). This configuration offers a double advantage with respect to configuration #1. It enables the tank to be located far away from the heat source. Moreover, the use of valves is no longer required. The arrangement of a thermal link between the storage tank and the evaporator may be difficult with this configuration. Hence, as the storage tank cannot receive heat from the evaporator, a secondary auxiliary heating system is therefore required to provide heat in order to desorb the fluid. The desorption needs to be performed before the LHP startup, as well as the cooling of the condenser. Once the storage tank is heated up, the desorbed vapor travels to the LHP, condenses in the condenser and flows to the evaporator. As soon as enough fluid is desorbed to supply the evaporator with liquid, the LHP can start. The storage tank and the vapor line being connected hydraulically, the pressure in both components are the same. The amount of fluid desorbed is function of the temperature of the tank that has to be chosen in order to ensure that a sufficient amount of working fluid is actually in the LHP. On the other hand, the depression generated by the condenser draws up the fluid from the evaporator and avoids it to come back to the storage tank. The connecting pipe between the LHP and the storage tank is thus full of stagnant vapor. During the operation of the LHP, the storage tank must be maintained at a temperature high enough to prevent the re-adsorption of the fluid that would occur if the adsorbent temperature was to decrease. So, in normal operation of the LHP, the power applied by the auxiliary heating system needs to compensate for the thermal losses of the tank to the ambient. During the LHP shutdown, the tank is no more heated. Its temperature decreases, which increases the adsorption capacity of the adsorbent that it contains. The

depression generated by the adsorption phenomenon draws up the fluid that flows to the tank where it is adsorbed and stored.

1.3. INTEGRATED STORAGE TANK (CONFIGURATION #3)

In the last configuration, the adsorbent material is directly placed in the envelope of the evaporator – compensation chamber. More precisely, it is embedded in the walls of the vapor collector (Figure 3). This solution avoids the use of valves and of an auxiliary heating system, but it requires a larger evaporator to contain the adsorbent material. Hence, the device is fully autonomous. When the LHP is stopped at low temperatures, the material adsorbs the whole working fluid. At the LHP startup, a part of the heat applied to the evaporator is transmitted to the adsorbent material by conduction through the evaporator wall (note however that the temperature of the adsorbent material is therefore lower than that of the evaporator wall). A part of the fluid can be desorbed due to that temperature rise, which enables the LHP operation. However, in normal operating conditions the temperature of the adsorbent material being lower than that reached with the previous configurations, its adsorption capacity is thus increased. As a consequence, for a given fluid charge circulating in the LHP, a larger amount of fluid in the whole device (LHP + storage tank) is required, which finally means a larger mass of adsorbent.

The advantages and drawbacks of the three configurations can be summarized as follows: the first configuration permits to benefit from the heat of the heat source to desorb the fluid thanks to the thermal link, but it requires controlling valves. The second configuration enables the tank to be placed far away from the heat source but it requires an auxiliary heating system to desorb the fluid and to extract heat at the condenser before the LHP startup. Finally the third configuration is fully autonomous but can only be used if enough space is available in the evaporator to contain the adsorbent material.

2. DESCRIPTION OF THE LHP AND WORKING FLUID CHARGE CALCULATION

In order to estimate the size of such an antifreeze system, a LHP presented previously [5] is considered. This LHP has a small evaporator because it is used to cool electronic components of an electronic board where the available space is generally small. Thus, the system is sized according to the second configuration, *i.e.* using a storage tank connected to the vapor line of the LHP, which enables the tank to be located where space is available.

The LHP is made of copper with a stainless steel compensation chamber to limit the axial parasitic heat flux (Figure 4). The 13 mm diameter cylindrical evaporator is welded onto a 9 cm² flat saddle, on which a heat power is applied. The 4 mm thick primary wick, made of sintered nickel powder, has pore radii equal to 7 μm. This cylindrical wick is drilled by a hole of diameter equal to 2 mm that forms the evaporator core. The vapor and liquid lines are 0.5 m and 0.63 m long, respectively, and have an external diameter of 2.4 mm. The condenser, 60 cm long, is welded on to a thin copper plate which acts as a heat sink.

The specifications of real LHP indicate a range of temperature in which the LHP must operate. Because of the water density variation with the temperature, as the LHP volume available for the fluid is fixed, there is a minimum ($m_{w,LHP,min}$) and a maximum ($m_{w,LHP,max}$) fluid charge. The fluid charge must then satisfy the relationships (1) and (2) assuming that the compensation chamber contains only water vapor in the coldest conditions and only liquid in the hottest conditions:

$$m_{w,LHP,max} = \rho_l(V_L + V_{wi} + V_V + V_G + V_C) + \rho_v(V_{cc}) \quad (1)$$

$$m_{w,LHP,min} = \rho_l(V_L + V_{wi} + V_{cc}) + \rho_v(V_L + V_G + V_C) \quad (2)$$

Where V_L , V_{wi} , V_V , V_G , V_C and V_{cc} are the volume of the liquid line, of the capillary wick, of the vapor line, of the vapor channels, of the condenser and of the compensation chamber, respectively and ρ_l and ρ_v the density of the liquid and the vapor, respectively.

To determine the fluid charge and properly size the LHP, a numerical modeling tool developed and validated previously [10] was used. Simulations were performed with water as working fluid, ambient and heat sink temperatures of 20 °C and a tilt angle between the condenser and the evaporator equal to 45 ° (evaporator located above the condenser). Simulation results indicated that for efficient operation, the fluid charge should be between 6.3 g and 7.5 g. Moreover, this model was used to plot the so-called "operating curves" (Figure 5Error! Reference source not found.) to ensure that the temperature does not exceed 100 °C at the evaporator, and to determine the evolution of the total thermal resistance with the heat input rate (Figure 6Figure 6).

3. ADSORBENT STORAGE TANK SIZING

The objective of this part is to size the storage tank associated to the LHP previously described. At first, an adsorbent material compatible with water and having the desired performance needs to be selected. Once this step is completed, the required material quantity for the application as well as the auxiliary heating system power, need to be calculated in order to size the storage device.

3.1. CHOICE OF THE ADSORBENT MATERIAL

The adsorbents used in industry usually have surface areas ranging from a hundred of $\text{m}^2\cdot\text{g}^{-1}$, even up to several thousands of $\text{m}^2\cdot\text{g}^{-1}$ [11]. They are porous materials with variable pore sizes. The most common industrial adsorbents are as follows (Table 1):

- ✓ activated carbons which are the most manufactured and industrially used adsorbents. They can be obtained from many carbonaceous materials (wood, charcoal, coconut, oil residues, etc.);
- ✓ zeolites that unlike other materials have a crystalline structure leading to regular and uniform size micropores;
- ✓ silica gels;
- ✓ activated aluminas.

The choice of an adsorbent depends on physical and chemical intrinsic properties such as its form (powder, granular, ...), its specific surface area, its porous volume, its apparent density (the mass per unit volume of a material, taking into consideration any voids), its resistance to mechanical and temperature stresses, its polar affinities (hydrophilic or hydrophobic), its adsorption capacity, its chemical compatibility with the adsorbate, its operating range, ecological and economic aspects, etc.

The adsorbed quantities at equilibrium for an adsorbate-adsorbent pair are typically presented under the form of adsorption isotherms. They represent the amount of adsorbate adsorbed at equilibrium as function of the pressure, for a constant temperature. They can be determined experimentally and are usually correlated by different mathematical models in the desired operating range (models of Henry, Toth, Langmuir, Langmuir-Freundlich, Dubinin-Polanyi, BET, ...).

Whatever the configuration, in this specific application the adsorbent material must fulfill several criteria. First, it must have a good affinity with water to reduce its volume. It must be able to adsorb water from the vicinity of the triple point (0.01 °C and 0.61 kPa) up to a temperature of about 100 °C (100 kPa). Indeed, the whole water must be adsorbed when the temperature is near 0 °C to avoid freezing in the device. In contrast at high temperature, enough water must circulate in the LHP to ensure a proper functioning of the device.

Among the various existing adsorbent materials, zeolites and silica gels are commonly used in adsorbent chillers operating with water. However, the various existing zeolites (13X, 5A, 4A and 3A) have a lower adsorption capacity with water than silica gel, typically about 20% of their dry weight in water. Silica gels have a better affinity with water [12-13] and are already widely used in many adsorption-based refrigerating systems. Their great polarity facilitates the adsorption of water on their surface. Moreover, owing to their high surface area, they have the ability to adsorb large quantities of adsorbate (up to 40% of their dry weight in water). Thus, silica gels are selected for our application as they appear as promising candidates and more specifically two commonly used adsorbents, namely, the Fuji Davidson A-type and RD-type silica gels [13].

Table 2 shows that these two types of silica gel have similar properties. However, the RD-type silica gel has a slightly larger specific surface area, a higher porosity and a better thermal conductivity than the A-type silica gel. Thus, the RD-type silica gel has better absorption characteristics than the A-type.

Conversely, the A-type silica gel loses a more significant portion of its adsorbent capacity on a same pressure range. In the following part, the sizing of the storage tank is carried out with the RD-type silica gel and at last compared to the A-type (cf. section 3.5).

In order to represent adsorption isotherms of these two materials in the range of operation considered in the present work, the Toth's model is recommended as the first choice because of its simplicity and its correct behavior over a wide range of pressure [12-13]. The Toth equation for the RD-type and the A-type silica gel is written:

$$q = \frac{A \times 10^{-10} \exp\left(\frac{B}{0.4619T}\right) P}{\left[1 + \left[C \times 10^{-9} \exp\left(\frac{B}{0.4619T}\right) P\right]^D\right]^{\frac{1}{D}}} \quad (3)$$

Where q is the fraction of refrigerant adsorbed by the adsorbent, T the temperature and P the pressure (expressed in kPa). The coefficients used are summarized in Table 3.

The amount of water adsorbed by the RD-type and the A-type silica gels as a function of the pressure is shown on Figure 7 and Figure 8, respectively.

3.2. DETERMINATION OF THE PIPE LENGTH BETWEEN THE LHP AND THE STORAGE TANK

The amount of working fluid that is actually desorbed for the LHP depends on the storage tank temperature. This temperature should be kept high enough to make effective the desorption and avoid any re-adsorption, but it should be as low as possible to avoid transferring heat by conduction along the connecting pipe from the storage tank to the vapor line. The length of this pipe must be properly sized to find out the proper trade-off. The minimum length is determined by considering the connecting pipe as a fin of infinite length, dissipating no heat flux at its end.

$$l_{cp} > \frac{2.65}{\sqrt{\frac{h_{amb} p_{cp}}{\lambda_{cp} A_{cp}}}} \quad (4)$$

Where l_{cp} , p_{cp} , A_{cp} , λ_{cp} are the minimal length, the perimeter, the cross-sectional area and the thermal conductivity of the pipe, respectively, and h_{amb} the ambient heat transfer coefficient.

The pipe is insulated with a 1 cm thick thermal foam of thermal conductivity equal to $0.07 \text{ W.m}^{-1}.\text{K}^{-1}$ (at the working conditions) to avoid any vapor condensation. Moreover, in order to limit the thermal diffusion along the pipe, stainless steel is selected due to its relatively low thermal conductivity ($\lambda_{cp} = 16.3 \text{ W.m}^{-1}.\text{K}^{-1}$). The conduction through the thermal foam, as well as convective and radiative heat exchanges to the ambient are taken into account to calculate the overall heat transfer coefficient. The pipe is considered as a horizontal cylinder. The ambient temperature and the emissivity of the thermal foam covered with a reflective medium are considered equal to $20 \text{ }^\circ\text{C}$ and 0.5 , respectively. As a result, the overall heat transfer coefficient is equal to $1.6 \text{ W.m}^{-2}.\text{K}^{-1}$. Thus a stainless steel pipe of a minimum length of 11.5 cm should be used to avoid transferring heat to the vapor line along the pipe wall. In real applications, a longer pipe could be used to locate the storage tank where space is available.

3.3. DETERMINATION OF THE AMOUNT OF ADSORBENT

Knowing the isotherms of adsorption of water on the RD-type silica gel and the total mass of fluid assuming that the mass of water vapor in the pipe is negligible in comparison with the fluid fill charge in the LHP during its operation, the mass of adsorbent can be determined. At $0 \text{ }^\circ\text{C}$, the whole charge of water (*i.e.* 7.5 g) must be adsorbed in the storage tank. The mass of RD-type silica gel and its

corresponding volume are determined as follows, using the apparent density indicated in Table 2Table 2:

$$m_{sg} = \frac{m_{w,LHP,max}}{q(0\text{ }^{\circ}\text{C})} \quad (5)$$

Thus, 16.6 grams of RD-type silica gel are required, which corresponds to a volume of 23.7 cm³. For example, if the storage tank has a cubic form, its edge is about 2.9 cm. Such a cube has an external heat exchange surface area of 50 cm². The comparison of the studied LHP dimensions with those of the storage tank indicates that the storage tank dimensions are small compared to those of the LHP, making it a very compact system (Figure 9Figure 9).

3.4. SIZING OF THE AUXILIARY HEATING SYSTEM

The auxiliary heating system aims at heating the tank to desorb the fluid that it contains. To enable the LHP startup and operation, a sufficient quantity of fluid must be desorbed before the startup of the LHP (*i.e.* 6.3 g, *cf.* section 2). The storage tank temperature required for the process of desorption to desorb the desired amount of water is deduced by calculating the adsorbed quantity of water as a function of the temperature at this pressure. Once this temperature is determined, the power that the auxiliary heating system has to provide to the storage tank can be deduced. To properly size the auxiliary heating system, the most unfavorable operating conditions are considered. The LHP must be able to dissipate up to 100 W while the evaporator wall temperature remains below 100 °C. Thus, the maximum vapor temperature is 100 °C, which corresponds to a saturation pressure of 100 kPa. As the pressure losses along the connecting pipe are negligible, the storage pressure is nearly the same, *i.e.* 100 kPa.

$$m_{w,LHP}(T) = m_{w,LHP,max} - m_{sg}q(T) \quad (6)$$

FigureFigure 10 shows the evolution of the fluid charge in the LHP as a function of the storage tank temperature at a pressure of 100 kPa. One notices that the storage tank has to reach 151 °C to desorb the desired fluid charge for LHP operation.

Once this temperature determined, the energy that has to be dissipated by the auxiliary heating system is calculated. In order to desorb the working fluid, this energy Q corresponds to the sum of the sensible heat and the heat of desorption. The sensible heat to bring the temperature of the tank to 151 °C is estimated by considering an initial temperature of the tank equal to 0 °C.

$$Q = (m_{sg}c_{sg} + m_{w,LHP,max}c_w)T_{100kPa} + m_{w,LHP,max}Q_{ads} \quad (7)$$

Where c_{sg} and c_w are the specific heat capacity of silica gel and water respectively, and Q_{ads} is the isosteric heat of adsorption (taken equal to 2800 kJ.kg⁻¹ as a typical value [14]).

As a result, 25.2 kJ are required for the desorption of the working fluid. For example, this energy corresponds to a thermal power of 140 W released in a time for desorption equal to 3 min (Figure 11Figure 11), which seems acceptable in many applications.

3.5. COMPARISON OF RESULTS OBTAINED WITH BOTH TYPES OF SILICA GEL

Figure 12 compares results of the sizing carried out with both types of silica gel: the RD-type and the A-type. The RD-type silica gel has more favorable adsorption properties than the A-type (*cf.* section 3.1), which enables to use less adsorbent material and reduces the tank volume. Indeed, the mass of RD-type silica gel required for the system to operate is lower than that of A-type by 11 %. Nevertheless owing to its larger variation of adsorption capacity with temperature (compare Figure 7 and Figure 8), a same quantity of fluid is desorbed at a lower temperature with the A-type silica gel than with the RD-type silica gel. The storage tank temperature is thus lower with the use of the A-type silica gel while the energy required by the auxiliary heating system with both types of silica gel is

roughly similar. Therefore, depending on the constraints associated with the application, one or the other of these two materials could be selected.

CONCLUSION

The present paper aimed at demonstrating the feasibility and the interest of associating an adsorption storage tank to a LHP so as to form an antifreeze system. It also aimed at providing an overall design of the system.

The process of adsorption can overcome the drawbacks associated with the increase of the volume of water as the working fluid when the LHP is stored at temperatures below the solidification temperature, which is of interest as water presents many well-known advantages. Several configurations were presented. One system is equipped with valves and a thermal link, one system is equipped with an auxiliary heating system and one system can be integrated in the LHP body. Whatever the configuration, the choice of the adsorbent material is crucial to properly size the device.

For the proposed application, the choice was made to connect the storage tank to the vapor line of the LHP by a simple pipe and to heat it by means of an auxiliary heating system. The RD-type and the A-type silica gels were considered as the adsorbent. The sizing showed that even under the most unfavorable operating conditions, the storage tank volume is acceptable and it requires moderate thermal powers to operate.

ACKNOWLEDGMENTS

The author would like to thank Dr. David Farrusseng of IRCELYON for his kind advices regarding the choice of adsorbent materials.

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Table 1: Typical properties of various types of adsorbent materials [11]

Adsorbent	Surface area (m².g⁻¹)	Pore size (nm)	Internal porosity	Apparent density (kg.m⁻³)
Activated carbon	400 - 2 000	1.0 - 4.0	0.4 - 0.8	300 - 600
Zeolite	500 - 800	0.3 - 0.8	0.3 - 0.4	600 - 750
Silica gel	600 - 800	2.0 - 5.0	0.4 - 0.5	700 - 800
Activated alumina	200 - 400	1.0 - 6.0	0.3 - 0.6	800 - 950

Table 2: Thermophysical properties of silica gels [12]

Property	RD-type	A-type
Pore size (nm)	0.8 ~7.5	0.8 ~ 5
Porous volume (cm ³ .g ⁻¹)	0.37	0.28
Micropore volume (%)	49	57
Mesopore volume (%)	51	43
Skeletal density (kg.m ⁻³)	2027	2060
Particle bulk density (kg.m ⁻³)	1158	1306
Surface area (m ² .g ⁻¹)	720	650
Average pore diameter (nm)	2.2	2.2
Apparent density (kg.m ⁻³)	700	730
PH	4.0	5.0
Specific heat capacity (kJ.kg ⁻¹ .K ⁻¹)	0.921	0.921
Thermal conductivity (W.m ⁻¹ .K ⁻¹)	0.198	0.174

Table 3: Coefficients for the RD-type and A-type silica gel

	RD-type	A-type
A	7.3	4.65
B	2693	2710
C	1.6222	1.1625
D	6	10

List of Figure Captions

Figure 1: Schematic of the device with valves and a thermal link

Figure 2: Schematic of the device with an auxiliary heating system

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Figure 6: Simulation results: thermal resistance vs. heat flux

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Figure 8: Isotherms for the A-type silica gel-water pair

Figure 9: Dimensions of the storage tank compared to the dimensions of the LHP (each component is displayed at scale)

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Figure 11: Power required by the heating system

Figure 12: Comparison of 2 different adsorbents: RD-type vs. A-type silica gel

Figure1
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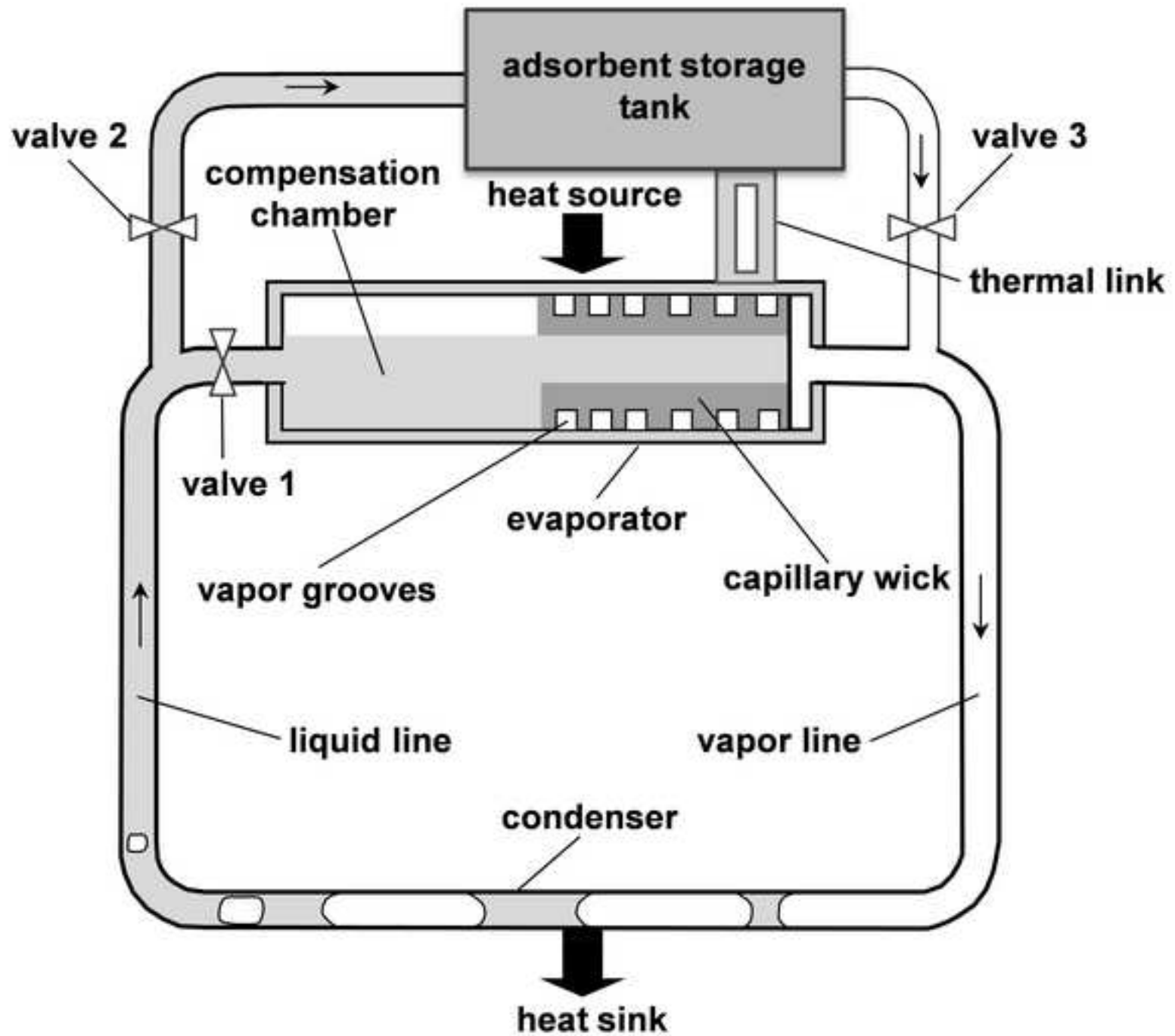


Figure2

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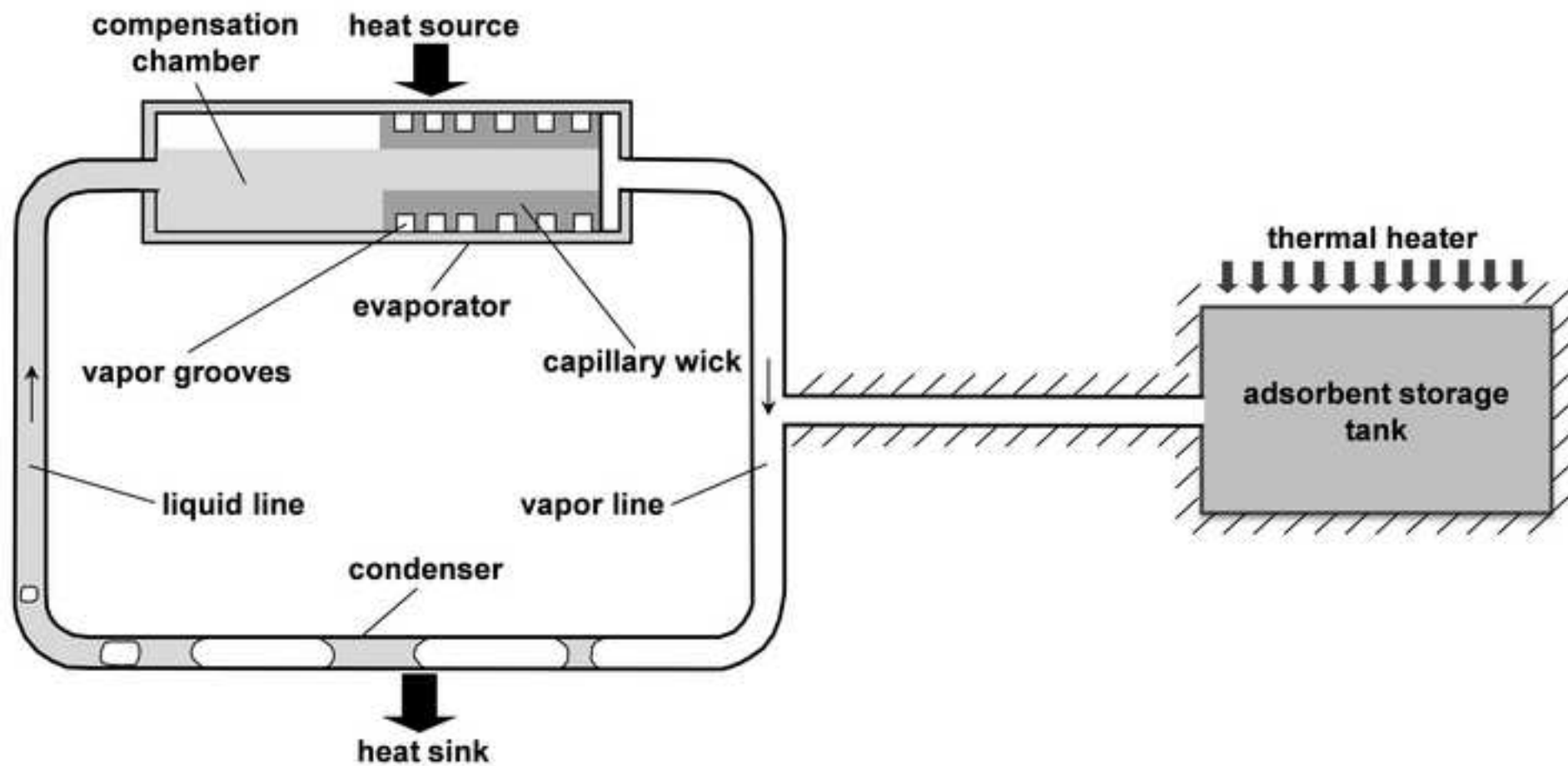


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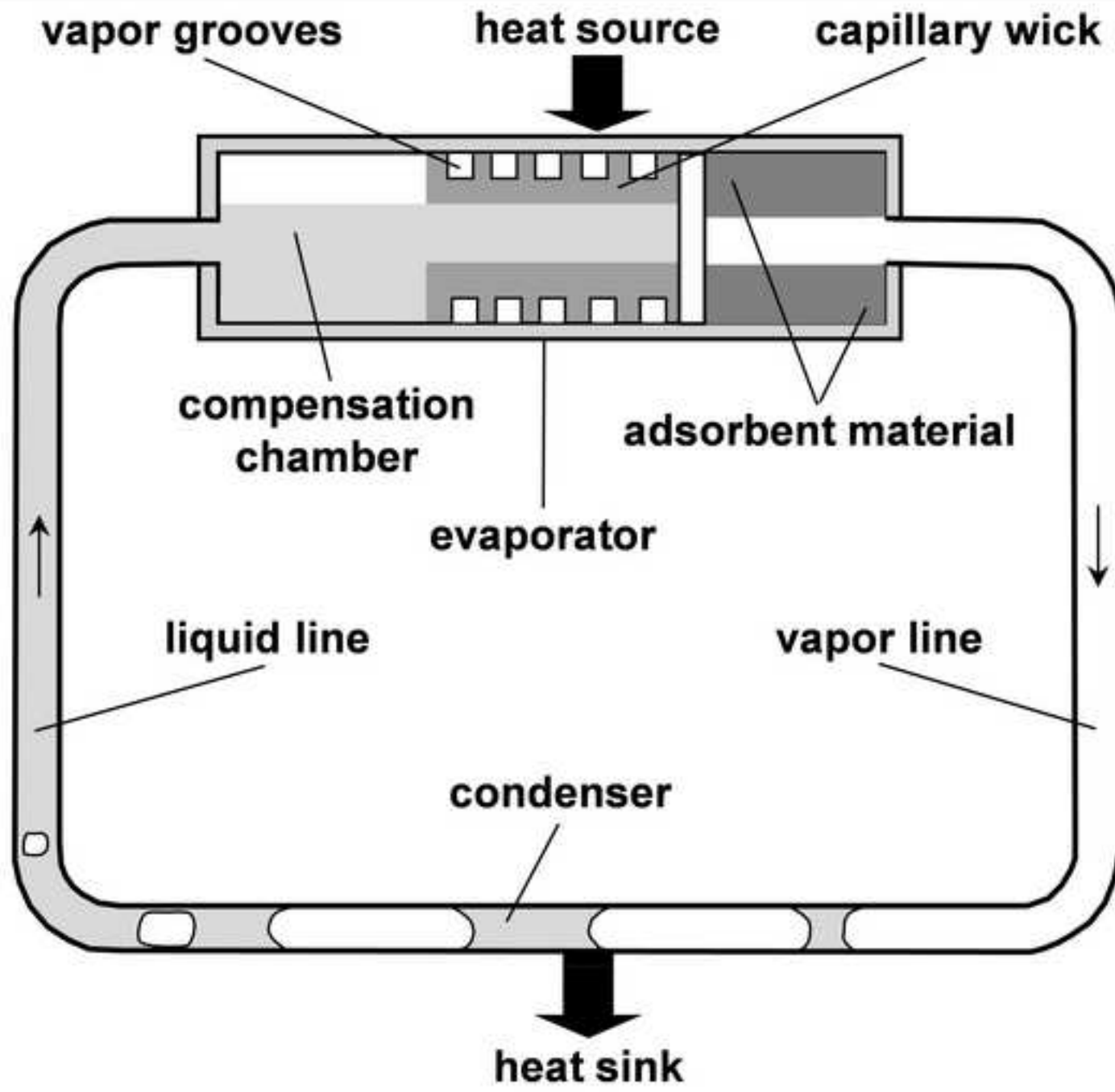


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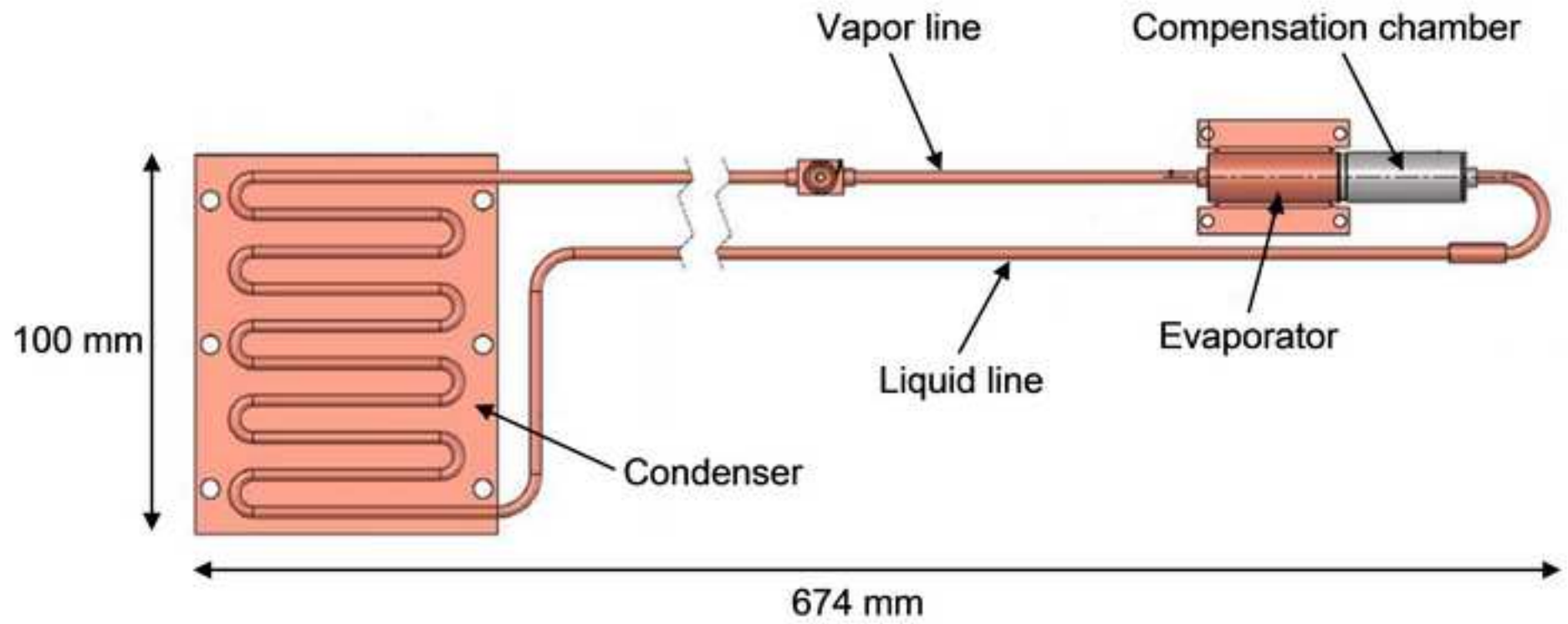


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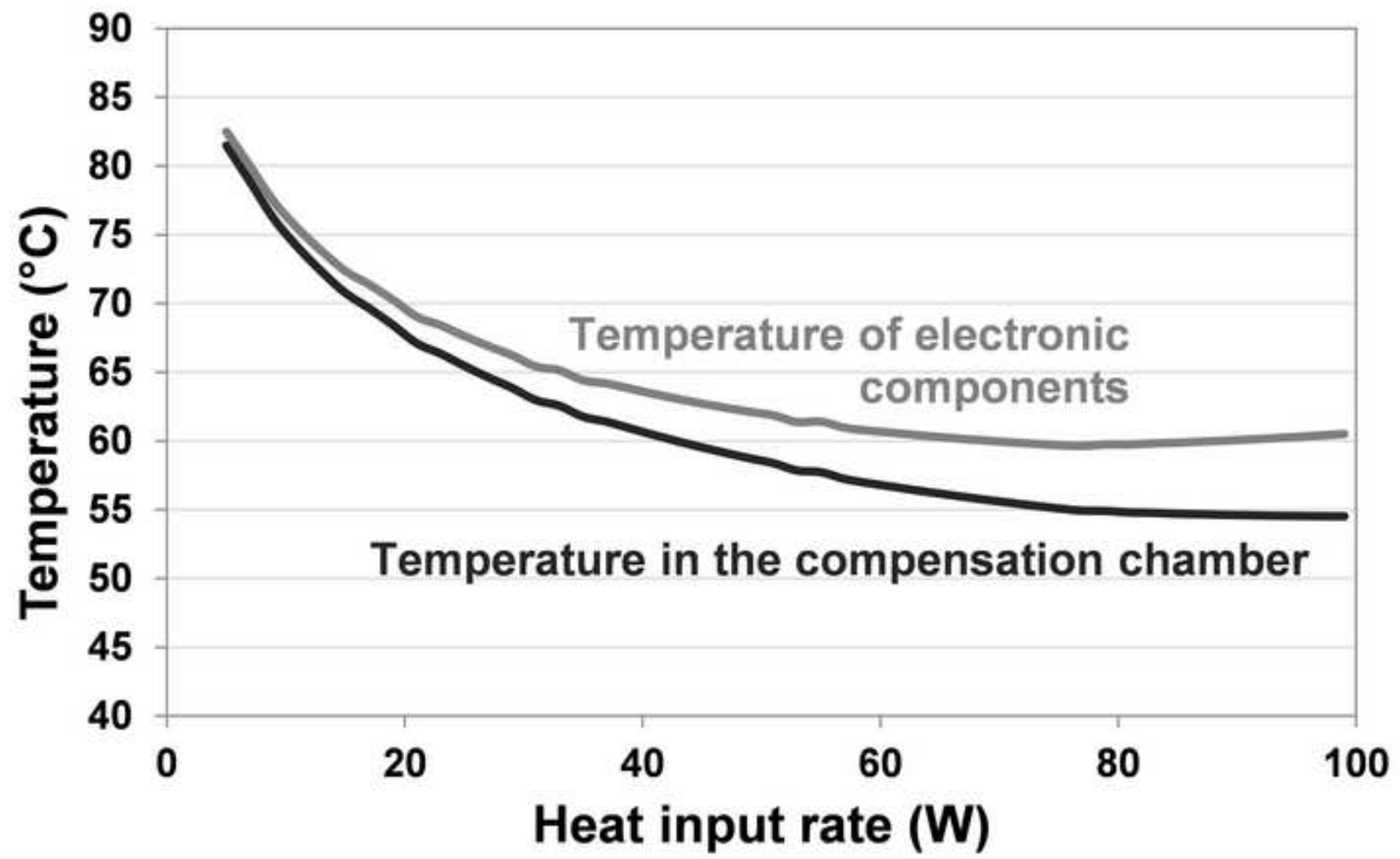


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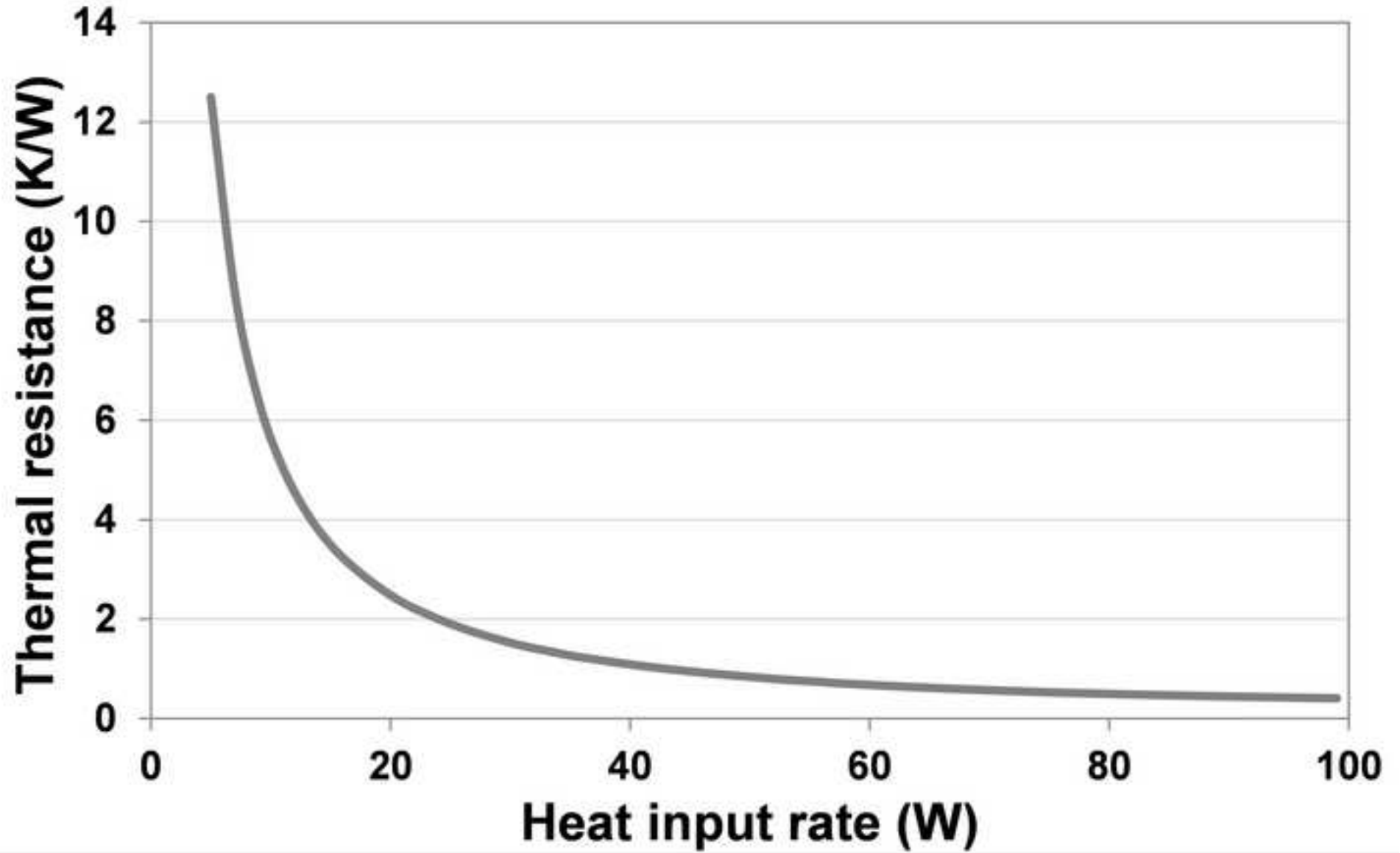


Figure 7

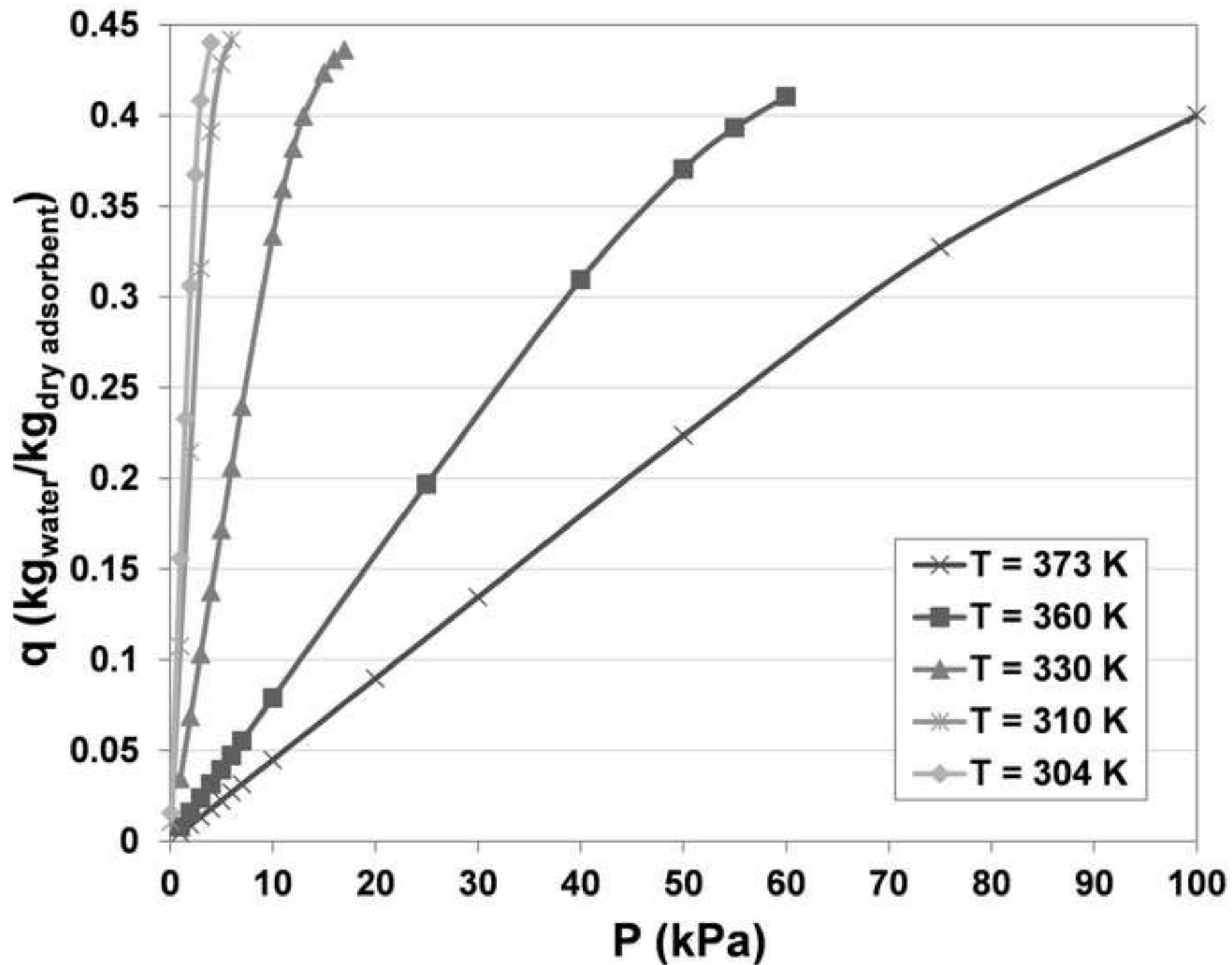
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Figure8

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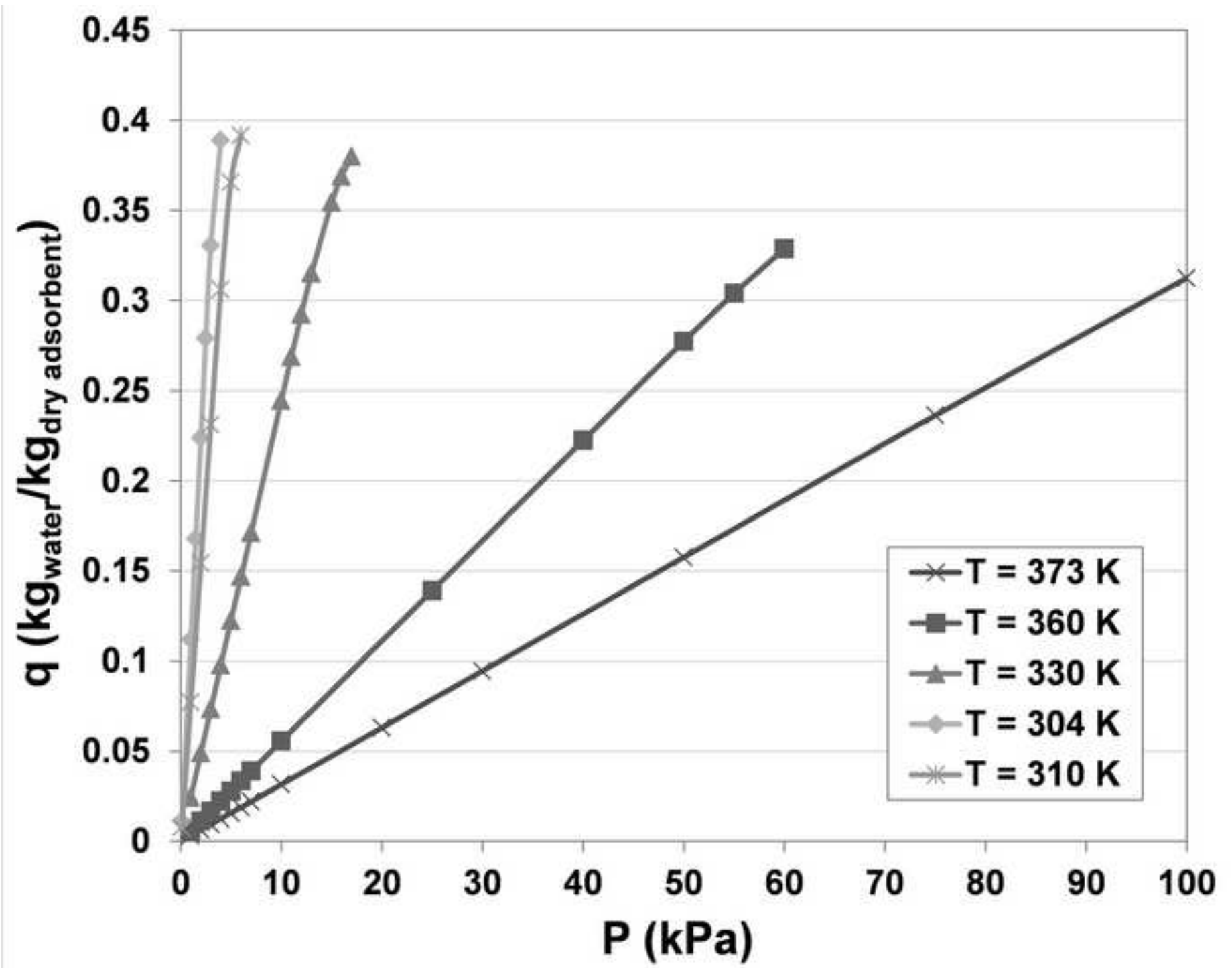


Figure9

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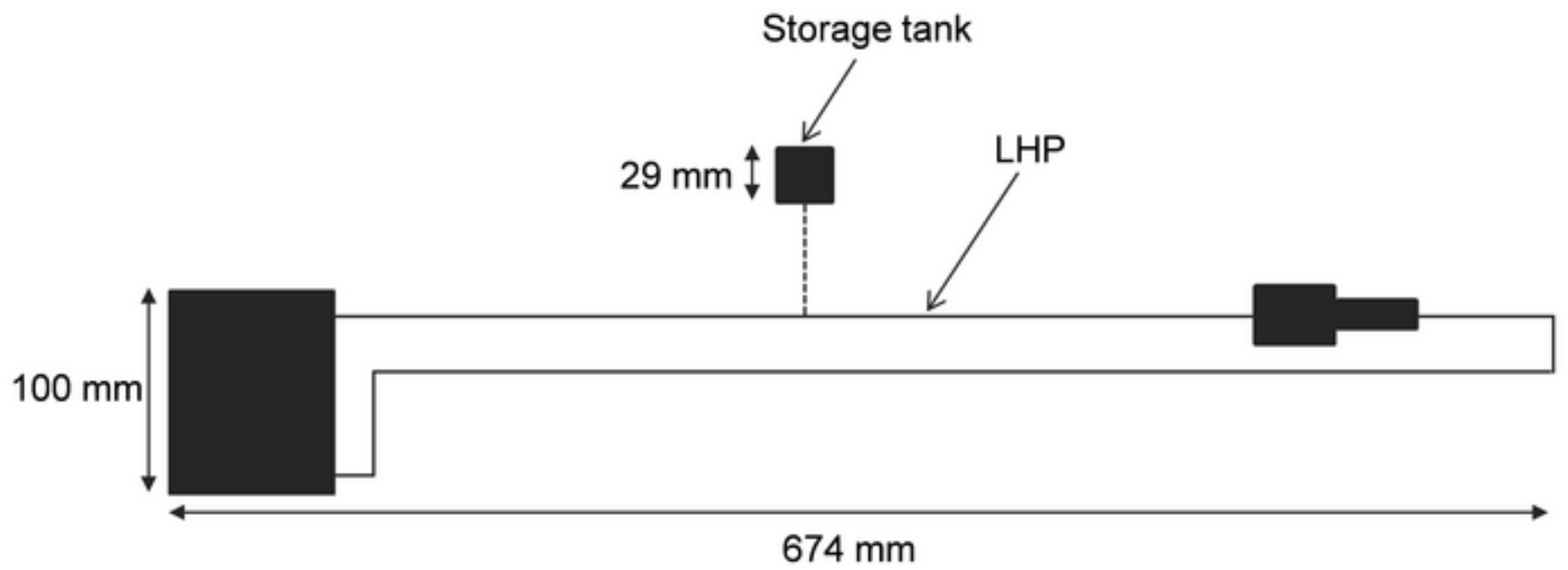


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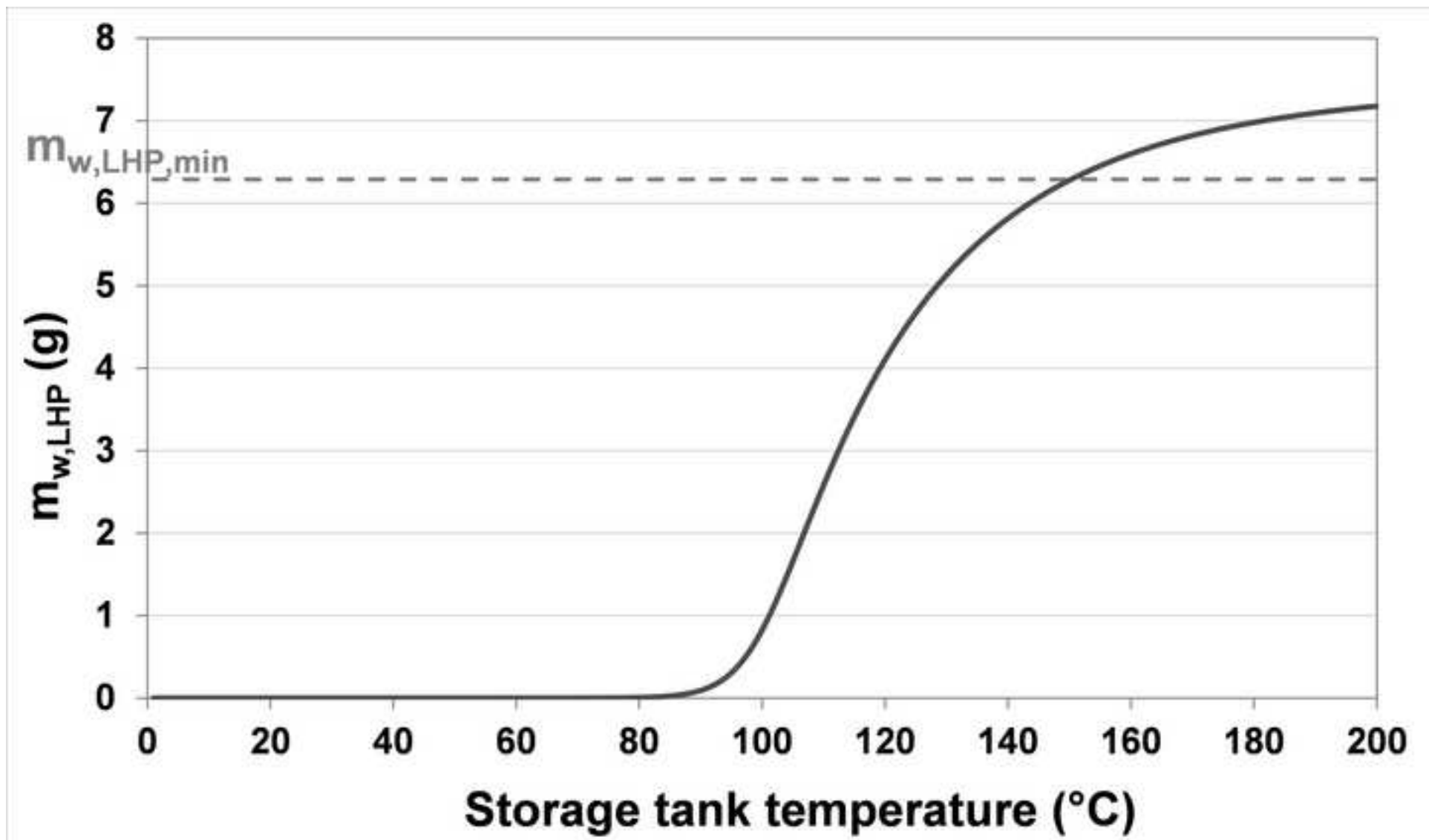


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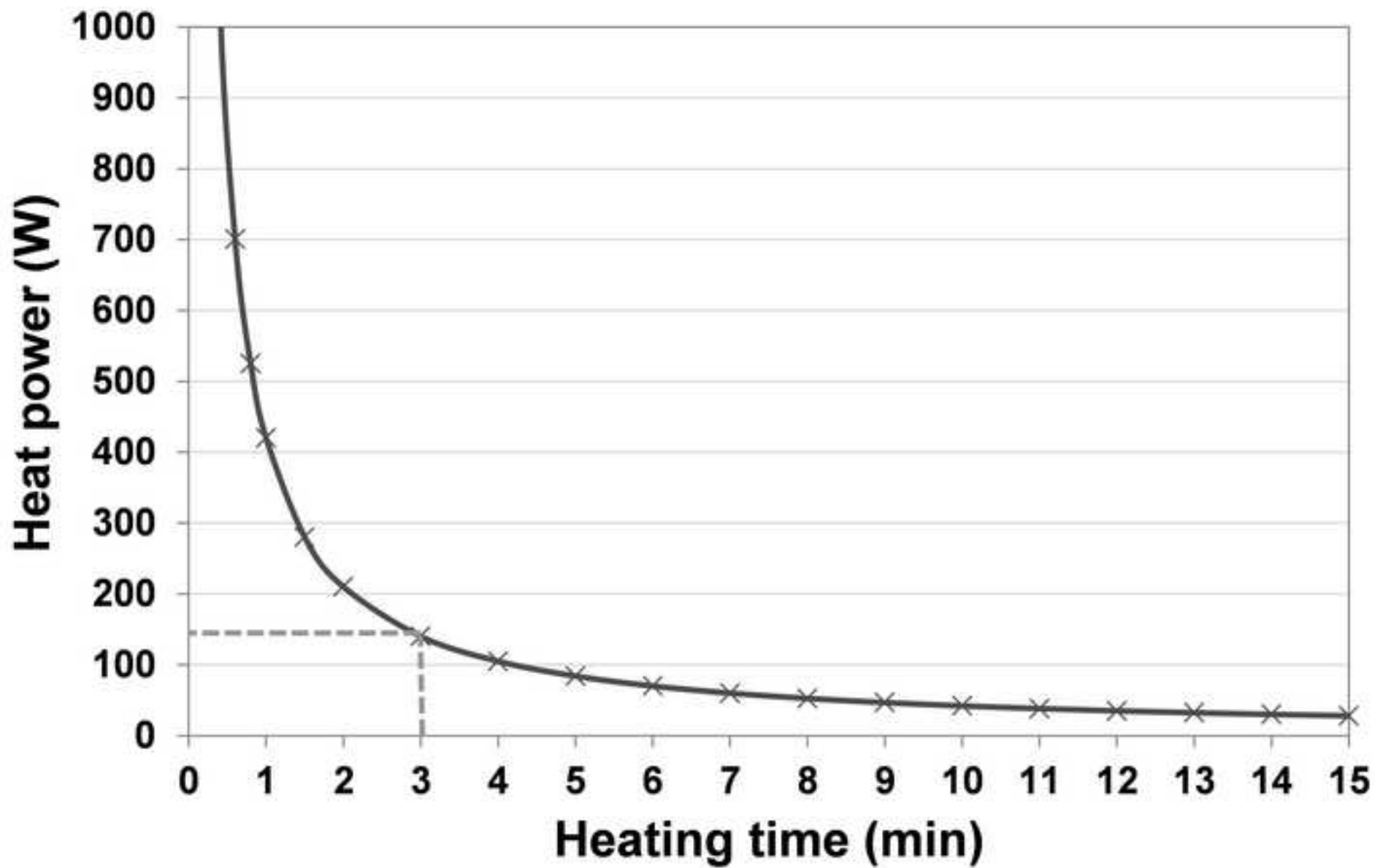


Figure12

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