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EXPERIMENTAL INVESTIGATION OF A HIGH EFFICIENCY ELECTRIC HEATER AND DEHUMIDIFIER PROTOTYPE UNIT

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ABSTRACT

In this paper the principle of operation and preliminary laboratory measurements of a prototype of a high-efficiency electrical air heater unit is presented. Unlike conventional heaters, which apply Joule-heat formed by electrical resistance, the developed device uses thermoelectric modules for heating ambient air. Just like in case of resistance heaters, most of the heat is produced as a result of the internal ohmic resistance of the thermoelectric module (resistance heating), however, in case of appropriate air conditions our device is capable of transforming the latent heat of the air moisture into heat energy. In case of condensation mode, some of the moisture condensates on the cold side of the module while its latent heat is transferred to the hot side of the module where it heats the dried air. In this mode, the heating efficiency of the device (e.g., the ratio of the heat added to air and the consumed electricity) is over unity. Following the idea and basic equations of the operation of this device, the results of the laboratory measurements in a climate test chamber is presented.

Keywords: latent heat, condensation, thermoelectric-module, heater, air dryer.

1. INTRODUCTION

In many cases electric heating is a cheap and convenient solution where relatively low heating power (up to some kW) is required. Although, the electrical power is relatively expensive compared to another primary energy sources (e.g. district heating, natural gas or firewood), in case of smaller rooms or additional heating the simplicity (consequently its low price) of an electric heater decides in its favour. In addition, most of the electric heaters use ohmic resistance on which the electric current produces Joule-heat: approximately the total amount of the electrical power transforms into heat (the efficiency of the energy conversion is about 100%). The released heating power (P_h) is proportional to the voltage (U) on the heater's resistance (R) and the current (I) flowing through it, or it can be expressed by using quantities of R and I or U and R (see Equation 1):

$$P_h = U \cdot I = I^2 \cdot R = \frac{U^2}{R} \tag{1}$$

As it was mentioned, the smaller electric heaters are mainly used in residential rooms (primarily in bathrooms, kitchens and bedrooms), as an additional heating. Especially, in bathrooms and kitchens, the average level of the humidity is relatively high compared to the other rooms, which means that the air contains a considerable amount of water in form of vapour. It is well known that the evaporation of the water requires a large amount of energy (in the order of $\mathrm{MJ/kg_{H2O}}$). This heat (so-called latent heat as referred later here) can be recovered by condensing a portion of the water vapour out of the humid air.
Our prototype is capable of utilizing the latent heat by condensing a part of the vapour of the humid air by cooling the local air temperature below its dew point (T_{dew}), within the device. The released heat is then applied to heat up the air leaving the unit. In order to cool down the air below its dew point (so that condensation occurs while its relative humidity $\varphi = 1$), so called Peltier thermoelectric modules are used in the prototype. These devices have simple setup: they consist of two parallel electrically insulating plates with high thermal conductivity and among these, several semiconductor elements are placed. Based on the

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Peltier's effect, heat energy is transferred from one junction to another if different kind of metals or semiconductors are connected and electric current is flowing through the circuit.
Since Peltier modules have internal ohmic resistance (R), they can be used as conventional resistive electric heaters, even if no condensation occurs on theirs colder plates (e.g. the air contains relative low amount of water vapour, thus its dew point is much lower than its temperature). In this operation case the electric heater's heating efficiency (η) is about unity as a conventional electric heater. If the device operates in a room with considerable humidity (i.e. its dew point is not so far below its temperature), condensation occurs on the colder side of the Peltier modules. Therefore, latent heat can be pumped to the hot side of the Peltier modules where it increases the temperature of the leaving, heated air. In this case, besides that the released Joule-heat increases the temperature of the air, the latent heat raises even further its temperature. Since the total energy input is the electrical power only, in case of condensation, the heating efficiency is greater than unity, $\eta > 1$.
The schematic diagram of the energy flow can be observed on Fig. 1.

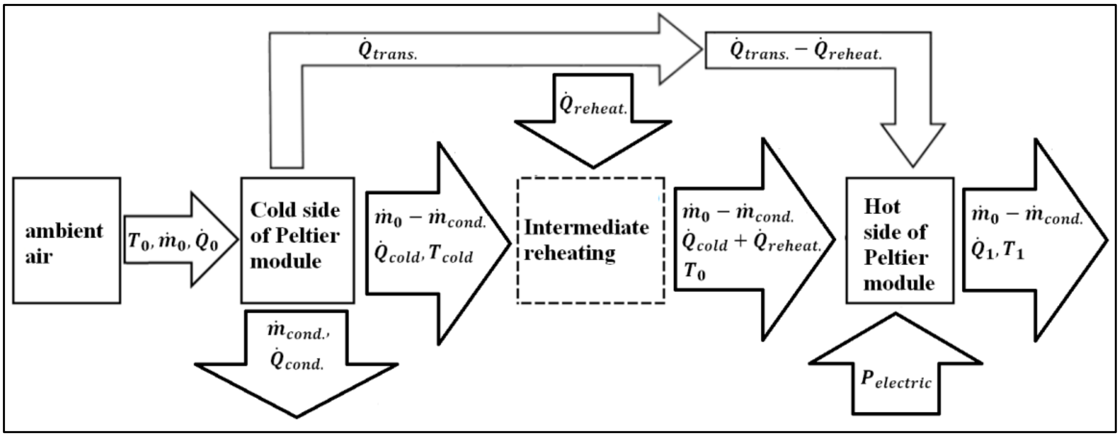

Figure 1. Schematic diagram of the heat and mass flow through the heating unit

Subscript "0" denotes the condition of the ambient air entering the unit, while subscript "1" corresponds to the leaving, heated (and in certain cases drier) air. T is the temperature, $\dot{m}$ is the mass flow and $\dot{Q}$ denotes the heat flow. Within the heater unit the temperature firstly decreases while condensation may occur ("*cond*" subscript denotes condensate). Following the cooled air gets to the hot side of the Peltier module where its temperature increases. In order to describe the process thermodynamically, an intermediate step is inserted (intermediate reheating, temperature up to T_0). In the next step the overheating of the air takes place, while the remained heat energy from the transferred heat ($\dot{Q}_{trans.}$) and the consumed electric energy of the Peltier module ($P_{electric}$) is added to the heat of the air. Based on these, it was possible to draw basic equations which were applied to perform preliminary calculations about the efficiency of the unit at different working conditions. For the calculations it was necessary to take into account the thermodynamic properties of the wet air entering the unit. The mass flow of the entering air ($\dot{m}_0$, see Equation (2)) is not constant when condensation occurs: the exiting mass flow ($\dot{m}_1$) is less than the incoming amount while the difference is the mass flow of the condensed water (condensate). Hence, for our calculations the constant mass flow of the dry portion of the wet air was used, and our results were presented with respect to the dry air.

$$\dot{m}_0 = \dot{V} \cdot \rho_0 \cdot \frac{1}{1+x_0} \tag{2}$$

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In Equation (2) $\dot{V}$ is the volume flow rate and ρ_0 is the density of the incoming air, while x_0 is the specific vapour content. The specific enthalpy of the wet air (h_{1+x}) is related to its energy content and it is a function of several quantities, such as the temperature (T), vapour content (x), etc. As Ref. [1] introduces, if the wet air cools down below its dew point (T_{dew}, where $\varphi = 1$), condensation occurs: the value of the specific vapour content decreases while a considerable amount of energy released due to the latent heat of the water. This heat is then pumped by the Peltier module to its hot side where the equipped heat sink transfers the heat to the air. By reheating the air to its initial temperature (and following above this value), one hand a lower relative humidity can be achieved (drier air) and on the other hand, for reheating, the required heat energy is less because of the air's lower vapour content.
Based on the foregoing, our idea, namely the air cooling while condensing a part of its humidity and then the reheating process using the recovered heat together the Peltier module's consumed electrical energy seems to be the key of a high-efficiency, relatively simple heater unit. First of all, detailed preliminary calculations were done in order to find the relations between the efficiency and several parameters (relative humidity, temperature, volumetric flow rate, temperature-difference of the Peltier module, etc.). Ref. [2] contains these calculations and dependence of the efficiency on the temperature and relative humidity. We found that in case of $\varphi_0 = 0.5$ the theoretical efficiency can reach the value of 1.1, while in case of $\varphi_0 = 0.7$ it increases value up to 1.3. Following the calculations, a prototype unit was designed and built. The operation of the unit was then investigated in a climate chamber at different air conditions (several temperature and humidity values were set while the heating performance of the unit was measured).

2. MATERIALS AND METHODS

A small prototype unit was designed which contains two Peltier modules connected in parallel and equipped with cooling fins on both cold and hot sides, a 12 V radial fan with speed-control (type JMC/DATECH DB9733-12HBTL), an Arduino® Uno panel with LCD display, relays, MOSFET transistor and 3 pcs DHT11 type thermocouple combined relative humidity sensors. Ref. [3] gives information about the applied TEC1-12706 type Peltier modules. Since the air was circulated with a radial fan, a case was needed in which the flow is directed in the appropriate way. For this reason, a case for the unit was designed and then 3D printed from ABS plastic. The disassembled prototype unit can be observed on Fig. 2.

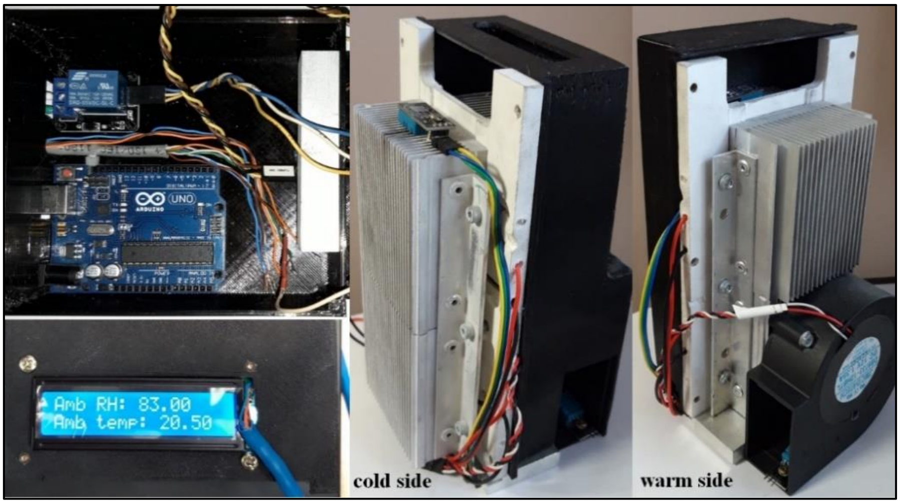

Figure 2. The main components of the heater: Arduino® unit, LCD display, cooling fins on the cold and warm sides of the Peltier modules, radial fan, humidity & temperature sensors.

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In Ref. [4] the design procedure and the assembly were described in details. The Arduino® Uno unit was necessary in order to the heater operates at the most suitably mode (i.e. with the largest available efficiency). Ref. [2] points out that the heating efficiency depends on several parameters. On the one hand the larger specific quantity of condensate the greater the efficiency is. Based on this, the cooler the cold side of the Peltier module, the higher the efficiency is. Unfortunately, the higher the temperature difference between the two sides of the Peltier module, the lower its efficiency is. This means that more electric power is required to keep a higher value of temperature difference which results lower ratio between the transferred heat and the heat released from the electric power. Because all of these, we kept the temperature difference as low as it was possible in which case condensation still occurred. For this reason, the rotational speed of the radial fan and the power of the Peltier modules were adjusted based on the relative humidity and the required temperature, controlled by a self-made, dedicated program ran on the Arduino® Uno. Ref. [4] contains the detailed construction and operation of the unit. The Peltier modules were controlled in hysteresis mode: theirs cold-side temperature was kept in the range of $(T_{dew} - 3\ °\mathrm{C}) \div (T_{dew} - 2\ °\mathrm{C})$, while T_{dew} was determined using the measured parameters T_0 and φ_0 and an empirical equation based on [1]. The temperature difference of the cold and hot sides of the Peltier modules was kept within the range of $15°\mathrm{C} \leq \Delta T \leq 20°\mathrm{C}$ while the voltage was set to $U = 10.5\ V$ while the current had the value of $I = 4.8\ \mathrm{A/module}$. This operating condition resulted the value of the cooling efficiency of the module in the range of $COP \approx 0.6 \div 0.7$ (estimated based on graphs provided by the manufacturer [3], while the ratio of the current and the maximum allowed current, $I/I_{max} = 0.79$).
The preliminary investigation of the heater was performed in a laboratory climate chamber with air volume capacity of $41.5\ \mathrm{m}^3$, temperature range of $+5\ °\mathrm{C} \div +43\ °\mathrm{C}$, with accuracy of temperature of $\pm 0{,}5\ °\mathrm{C}$. The relative humidity of the chamber is adjustable in the range of $\varphi = 30\% - 95\%$ with accuracy of $\pm 4\ \%$. For the measurements three different nominal values of relative humidity was set: $\varphi = 50\%, 70\%, 90\%$. In case of each humidity setting three different values of nominal air temperature were set: $T_0 = 14°\mathrm{C}, 18°\mathrm{C}, 22°\mathrm{C}$. These resulted nine different parameter settings altogether. Since condensation occurred in the most parameter settings, it was necessary to estimate the releasing latent heat. For this reason, the quantity of the condensed water was measured using a precision laboratory scale.
During the measurements the cooling fins were directed vertically (see Fig. 2) so that the condensate drops could slip into a small pot. To prevent the drops to adhere on the fins, a special super-hydrophobic coating was sprayed on the cooling fins. At each parameter settings, each measurement took adequate long time (one hour) to get enough amount of condensed water that it can be measured with a sufficient degree of accuracy. Furthermore, a certain time was required to get stationary state of the device (i.e. equilibrium temperature of the heat transfer). Following the measurement, by knowing the elapsed time and the mass of the collected water it was possible to calculate the mass flow of the condensed water ($\dot{m}_{cond}$), from which the released heat power ($\dot{Q}_{extra}$) was then calculated using Equation (3):

$$\dot{Q}_{extra} = \dot{m}_{cond} \cdot r_{H2O} + \dot{m}_{cond} \cdot c_w \cdot (T_{dew} - T_{cc}) \qquad (3)$$

where

r_{H2O} is the heat of vaporization of water at the temperature of the dew point (T_{dew}),
c_w is the mean specific heat capacity of the water within the range of $T_{dew} \div T_{cc}$,
T_{cc} is the temperature of the cooled condensed water on the cold side of the Peltier module.

Since the temperature of the cold side of the Peltier modules was kept in the range of $2 \div 3\ °\mathrm{C}$ below the dew-point temperature, the second product in Equation (3) yields only less than 0.5% extra heat related to the heat released from the phase-change (first product in Equation (3)).

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3. RESULTS AND DISCUSSION

The measured mass flow of the condensate at different parameter settings can be seen on Fig. 3 a.), while the part b.) shows the extra power due to the condensation.

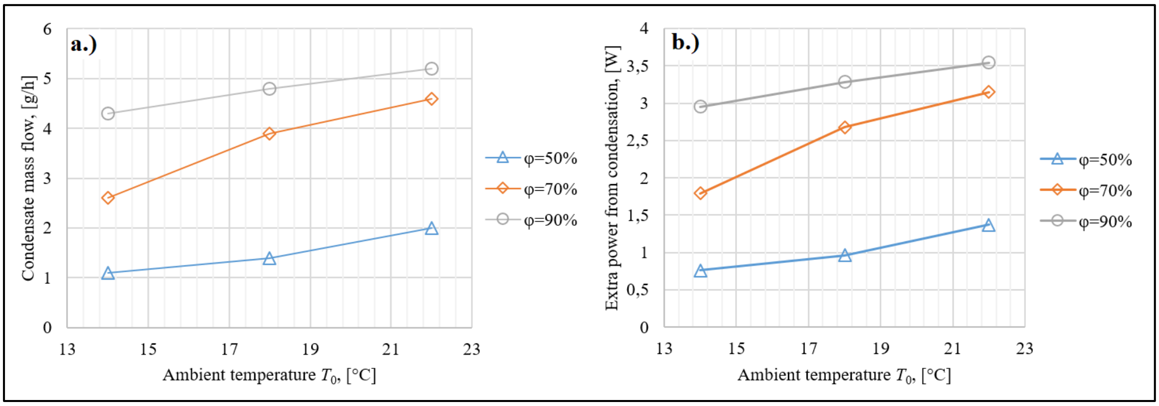

Figure 3. a.) The mass flow of the condensate and b.) the released extra power due to condensation as a function of different air condition (ambient temperature and relative humidity(φ)) settings.

Based on Fig. 3 it can be stated that the mass flow rate of the condensate and hence, the released extra power increases with ambient temperature in all three humidity settings. At a given temperature, higher value of the humidity resulted higher value of mass flow rate of the condensate which means higher released heating power. These all means that the heating efficiency of the developed heating unit increases with both the increasing initial humidity and both with the increasing ambient temperature.

In order to calculate the heating efficiency, monitoring of the electric power demand of the heater unit would have been necessary however, it was not possible to measure such quantity during the measurement. The voltage and the current of the Peltier-module pair were measured as it was mentioned before (with Arduino® module), hence the power consumption of the modules had the value of $P_{electric} = 100.8$ W. However, this value changed with time thanks to the switching program ran on the Arduino® unit which controlled the modules in hysteresis mode (i.e. they were switching on and off depending on the temperature). If we suppose that the modules would have operated continuously during all parameter settings, the heating efficiency can be underestimated. Hence, obviously new measurements are required in the future while the electric power demand as a function of the time has to be acquired.

The definition of the heating efficiency of this device is not obvious. On one hand, the efficiency can be defined as the ratio of the useful energy/power and the total introduced energy/power. In case of this device the introduced power is mostly the power of the Peltier modules, however the Arduino® unit and the fan have electric power demand as well from which the power of the Arduino® unit can be omitted. Since it was not possible to measure the power consumption of the fan (moreover its speed was controlled), in our definition the introduced power equals the electric power demand of the Peltier modules ($P_{electric}$). The useful power can be defined as the power which heats the air. This power nearly equals to the sum of the introduced electric power of the Peltier modules and the power yielded from the condensation of the moisture and the heat extracted by cooling the condensate. Following this approach, Equation (4) shows the definition of the efficiency:

$$\eta = \frac{P_{electric} + \dot{Q}_{extra}}{P_{electric}} \tag{4}$$

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Based on the Equation (4) and supposing constant power demand of the Peltier modules, the efficiency of the unit as a function of the humidity and temperature can be observed on Figure 4.

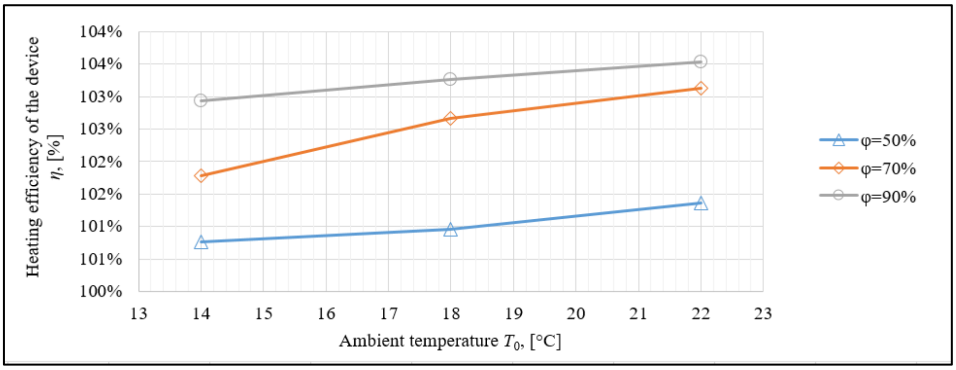

***Figure 4.** The underestimated heating efficiency of the unit as a function of the relative humidity (φ) and the temperature of the air (T_0).*

Based on Fig. 4 it can be noticed that values of efficiency greater than unity were calculated in all measurement cases however, the efficiency was surely underestimated in our calculations. The real efficiency values are supposed to be greater at the corresponding measurement cases: the power demand of the Peltier modules were not constant (duty cycle < 1), the time averaged power should be less than that of was used in Equation (4). Besides this, the real quantity of the condensed water (along with this the released extra power) was slightly greater than that of presented on Figure 3a: some droplets were stuck on the heatsink. Nevertheless, these remarkable values are the result of the heat released from the condensation, since it ensures greater value of the numerator in Equation (4) than the value of the denominator. The efficiency increases both with the initial temperature of the air and it increases with the relative humidity. This phenomenon can be explained by the amount of the condensable vapour per unity air volume, which increases both with the relative humidity and with the temperature as it can be seen on Figure 5.

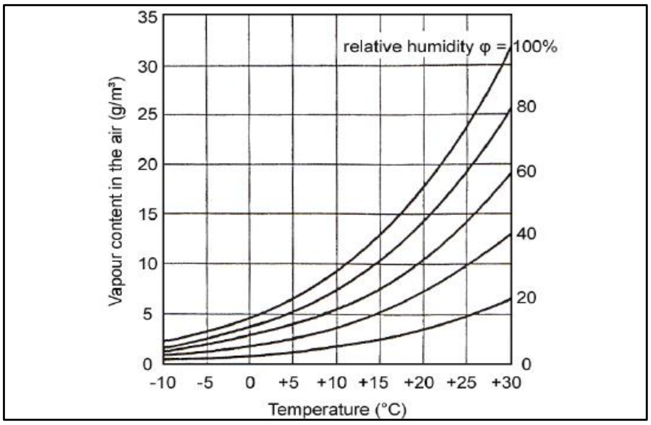

***Figure 5.** The relationship between temperature, vapour content and relative humidity [5]*

Since the developed device utilizes the extra heat released from the condensation, the more condensed vapour per unity time the higher its efficiency is.

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Unlike the former definition of the heating efficiency, different approach can be introduced, the efficiency can be defined more freely as the ratio of the usefulness and the investment. In our case, the extra heat is not the only yield of the developed device. Another important advantage of this unit is that it reduces the moisture content of the air. Since the water vapour represents a huge amount of energy (i.e. the amount of the heat of vaporisation of the water is significant), at a given temperature the specific enthalpy of the air-vapour mixture can be significantly reduced by reducing its vapour content. This means that by cooling down the air on the cold side of a Peltier module, and in this way by condensing a part of its vapour content, the drier air can be reheated to a higher temperature by introducing the same amount of heat which was extracted on the cold side. Notice that, in spite of the fact that up to this point there was no external heat added to the air medium, its temperature became higher. If extra energy (electrical energy which drives the Peltier modules, released energy from condensation, and the extra energy released by cooling down the condensate) is added to this – drier – air with lower specific enthalpy, its temperature even more increases. In this approach we would get even higher values of efficiency, however this efficiency would require a more complex definition.

4. CONCLUSIONS

It was found that our novel design, heat pump type heater unit can be applied as an air heater with heating efficiency higher than 100%. The results of the performed experiment proved that based on the operating principle (e.g. condensation of the vapour of the ambient air) it is possible to achieve more economical heating compared to the popular resistive, electrical heating technique. Based on the results, - considering the possible achievable higher efficiency - an example for the primary location of the application of this device are wet rooms, e.g. bathrooms, kitchens. Forthcoming experiments will include continuous acquisition of the power demand of the unit for more precise calculation of its efficiency during different operating conditions. Since the efficiency can improve by fine tuning of both the values of the temperature of both the cold and the hot sides of the Peltier modules.

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