Smart Dryer

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1. Abstract

Washing and drying clothes is a necessary everyday activity. A Istat statistical survey state that 96,2% of Italian family have a washing machine while only 3,3 % have an automated dryer. The reason why so few families own an automated dryer is that, although this appliance allows for fast drying of the clothes, it has a considerable economic weight both for purchase and for consumption. The remaining part of the families still use simple drying racks because they are cheap and do not consume. They are a good way to dry clothes on sunny and breezy days, but they are very inefficient during the darkest and coldest times of the year. This results in very slow drying times. This turns out to be a problem especially for large families, where generally one washing machine load is not enough to dispose of all the laundry.
Our study aims to create a low-cost smart system to optimize this process.

2. Introduction

Based on these existing models, we assessed what features our model would have to have in order to compete with them and provide something new on the market. We thought of a project suitable for those people who want to solve the problem of drying clothes, without investing excessively on it, and we thought of "decorating" the classic drying rack that every family has at home, with modules that can guarantee the efficiency that it demonstrates outdoors on typical breezy days. These modules must be comfortable to hang, it must take up little space, it has to make little noise and have low consumption. In this way they can compete strongly with existing models, re-establishing the needs of those who do not intend to invest in a totally new drying system, but simply by 'enriching' their simple drying rack, obviously at a low price.

The approach to the problem was initially of a theoretical type, through the study of physical models capable of describing the thermodynamics of the process, and later empirical tests were carried out for the collection of data and the verification of the effectiveness of the drying system.

3. Related Works

There are already several devices designed to solve the problem of drying clothes.

The first, the simplest, is the simple drying rack. The idea is to hang the clothes so that the entire outer surface of the clothes is exposed to the external environment. So, this simple device exploits three fundamental parameters for drying: complete exposure of the cloth to external contributions, heat and the convective motion of the air. The problem is that while the first parameter is controllable through a good drafting of clothes, the second and third are beyond human control, therefore it turns out to be inefficient during cold days. The strong points of this device are the economy and the zero consumption, a significant weak point is the inefficiency during long periods of the year.

The second device that has been developed for this purpose is the dryer. The clothes dry thanks to a heat source which heats the air and introduces it into the drum through a fan. The advantages of the dryer are considerable from the point of view of efficiency and drying speed, thanks also to programs that can be adjusted according to the load and type of cloths. In this case, a significant weak point is the high price, the high consumption and the size.

The third device designed to solve the problem of drying clothes is the electric drying rack, and it is the one that comes closest to our project. The electric drying rack, based on the type of operation used, has different drying systems. There is the model with heated rods, the type that instead uses forced ventilation, hot or cold, and the one with a heat chamber.

4. System Description

4.1 Physical Analysis

We studied deeply the drying phenomena and the dynamic of our system and even create a simple model to simulate it on Matlab, but in the end the most useful results for the implementation of our dryer were found in papers on drying phenomena [1] [2]: and they can be summarized in these two concepts:

- the drying process is faster if the air around clothes have higher temperature is dryer and is faster.
- the moisture content can be approximated as a linear function of time:

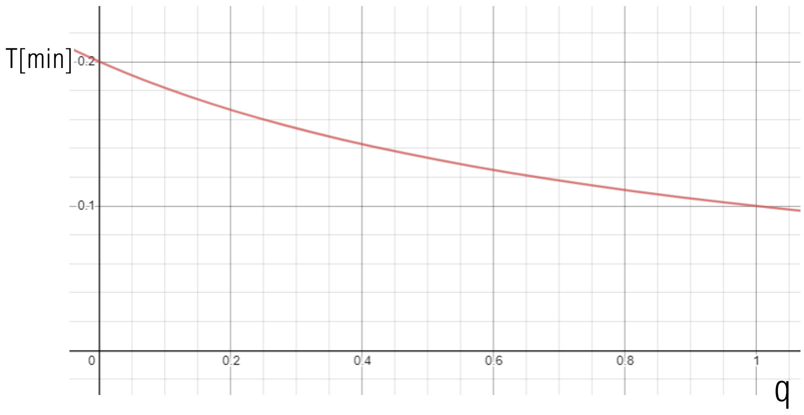
$$m(t) = -C(T,V_{air},RH)t + m_0$$

Where $C(T,V_{air},RH)$ is the mass transfer coefficient, we tried to exploit the dependence but, in the end, an empirical approach to the problem it's easier and sufficient to implement the system.

From $m(t) = -Ct + m_0$ we can calculate the total time to dry the clothes: assuming that when the drying system in on C change from C_{off} to C_{on} and also that the system operate intermittently; in an period T_{period} it will be on for T_{on} and off for T_{off}. By carrying on the calculation:

$$T_{tot}(q) = \frac{m_0}{qC_{on}+(1-q)C_{off}} \text{ where } q = \frac{T_{on}}{T_{period}} = \frac{T_{on}}{T_{on}+T_{off}}$$

By drawing $T_{tot}(q)$ we can understand an important thing about the system



With:

$m_0 = 1\ g$

$C_{on} = 10\ g/min$

$C_{off} = 1\ g/min$

Just example value not real one

Fig.1 Trend of drying time over q

As we can see a minimum does not exist meaning that all the energy given to the drying system is effectively used to dry the clothes: there's a trade-off between drying time and consumed energy. We decided to let the customer choose between three modalities with different drying and energy efficency that will be discussed in paragraph 4.4.

4.2 System Specification

Functional specifications
The system must:

- make the drying process faster,
- understand when the clothes are dry,
- notice the user that the clothes are dry.

Non-functional specifications.
In order to be competitive with other product the system must be:

- cheap: less than €150.
- small: easy to move and to keep in small home.
- energy and time efficient.
- adaptable for different drying rack.
- user friendly: easy to use.

4.3 General Architecture

The system will be composed of multiple module each of them with this architecture:

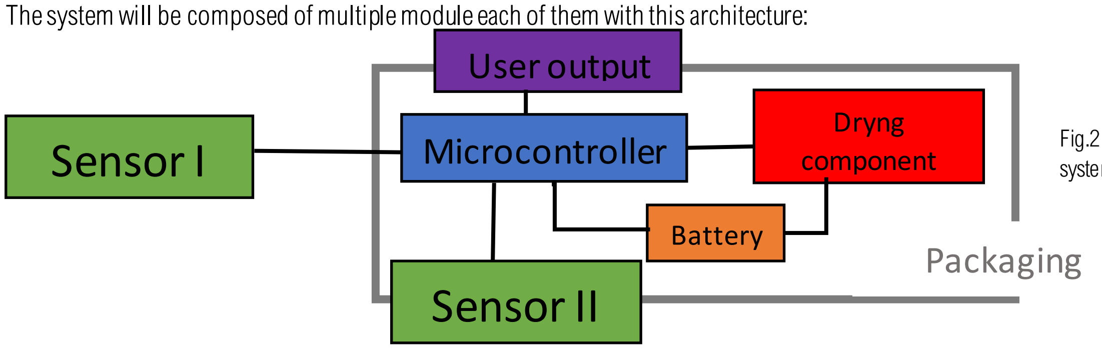


Fig.2 Schematic representation of the system

A module is composed of five parts: the microcontroller, two sensors, the drying system, the power supply, the output to communicate to the user that the clothes are dry and choose the modality.

The sensor I must be placed inside one of the clothes to evaluate the drying, so it will be connected to the microcontroller with a long cable, and it will be possible to place it in the clothes using a clothespin attached. The sensor II is needed to measure the environment condition to identify if the drying is complete.

4.4 System Characteristics

A module will cover just a portion of the rack, the customer will need multiple modules to cover all the rack, in this way th e module will be small enough to be applied to different type of rack and different amount of clothes.

Fig.3 Possible positioning of the module on different drying rack

We chose as drying component a fan because they are cheap, easy to use, quiet and can be found of different size.
The fan is oriented downwards so that the air flows into the space between the clothes. The air flows push away the humid air near clothes and speed up the drying process, also the air between clothes is colder that the air pushed inside by the fan so the temperature will also be higher speeding the drying process.

Since each module have only one sensor and operate on multiple column of clothes, we assume that each column will have the same condition and will dry in the same time. This of course is not true since there are different type of clothes; so in the user manual will be specified to put the sensor inside the heaviest clothes for example: jumpsuit, sweathshirt or towel so that if the heavi est clothes are dry also the ligheter one are dry.

The fans will work under the control of temperature and humidity sensors. The clothes are dry when the relative humidity of the air near the clothes RHc is equal to the relative humidity of the environment RHe. From the experiment we notice that the clothes feel dry by touching them even if RHc=RHe+10. So the module operate until RHc=RHe+10.

As said in the theory we let the customer choose between three modalities:

- fast drying: fan always on until the drying is complete;
- normal regime: 5 minutes on and 5 off, repeat until the drying is complete;
- energy saving: 3 minutes on and 9 off, repeat until the drying is complete.

From theory $T_{tot}(q) = \frac{m_0}{qC_{on}+(1-q)C_{off}}$ with $q = \frac{T_{on}}{T_{on}+T_{off}}$

Consumed energy: $E(q) = P * T_{on} * number\ of\ cycle = PqT_{tot}(q)$

Calling $\eta_T = \frac{T_{tot}(q=0)-T_{tot}(q)}{T_{tot}(q=0)} = 1 - \frac{C_{off}}{qC_{on}+(1-q)C_{off}}$ the time yield, that represent the percentage of time saved respect to ordinary drying; calling $\eta_E = \frac{E(q=1)-E(q)}{E(q=1)} = 1 - \frac{qC_{on}}{qC_{on}+(1-q)C_{off}}$ the energy yield, that represent the percentage of energy saved respect to the case fan always on; for the different modality their value are:

- fast drying q=1: $\eta_T = 0{,}83,; \eta_E = 0$;
- normal regime q=0,5: $\eta_T = 0{,}7;\ \eta_E = 0{,}15$;
- energy saving q=0,25: $\eta_T = 0{,}54;\ \eta_E = 0{,}34$;

It will be possible to change the modality during the drying.
Those yields are just theoretical value that must be taken as a reference, in fact they depend on the ambient and can vary for different case. To calculate them we found C_{on} and C_{off} experimentally, as discussed in paragraph 6.

The module will have rechargeable battery so no battery changing; that is because the module can operate for more or less 6 hour (this time is calculated with the prototype fan P=10W, V=12V, and considering a 12 V rechargeable battery of 4800mAh) which is sufficient for 2-3 cycle so changing the battery every 2-3 cycle would be costly and bothering for the customer.

The user output is made of a led that lights when the drying is complete, a led that will blink where the battery is soon to be flat and a potentiometer to change the modality.

5. Prototype

For our prototype, the microcontroller is Arduino Uno which is connected with jumper wires to a breadboard connected to all the other part of the system.

The relative humidity in the system varies on an interval of 30%-100% and the temperature of 0°C- 40°C. Relative humidity and Temperature vary slow during the drying process, so we do not need a fast sensor; but we need a cheap and small sensor with a big range and a good sensibility, that work at room temperature. We choose the DHT11, which has an operating voltage of 3.3-5 V DC, a measurement range of 20-95% for the relative humidity and 0-50°C for the temperature with a sensibility of $\pm$ 1% for humidity and $\pm$1°C for temperature; so compatible with our request.

Fig.4 Humidity sensor

The criteria to choose the fan are:

- The air flow: it must significantly reduce the drying time.
- The energy consumption: since it must operate for a long period of time it must have a low energy consumption.
- The alimentation voltage.
- The size: sufficiently small to be moved easily but sufficiently large to cover multiple rag.
- The noise: a noisy fan could be annoying to the customer.
- The cost.

We choose the Sunon MEC0381V1-A99 which has a great air flow (234 m^3/h), a good dimension: 12x12x3,8 cm (can cover 2-3 rack of an ordinary drying rack) and is quiet: 50 dB. The downside are: the cost (14,80€ on amazon 7,86€ on digi-key Italy), the alimentation voltage: 12V; so it must be powered separately from Arduino and it must be controlled with a MOS; we used the IRF520.

Fig.5 Sunon MEC0381V1-A99 fan

Even though exist 12V rechargeable battery (for example the super rechargeable DC12480 li-ion Battery that cost 14 euro) we used a 8XAA battery holder to power the fan; in the real module the power source will be a 12V rechargeable battery. Arduino is powered by the computer. In the real system we will need a switching voltage regulator (because we have a high-power consumption) to power the microcontroller. The microcontroller and the battery are be placed beside the fan to avoid interference with the air flow. The system will be packed inside a light waterproof material with hole above and below the fan. For out prototype we used a box.

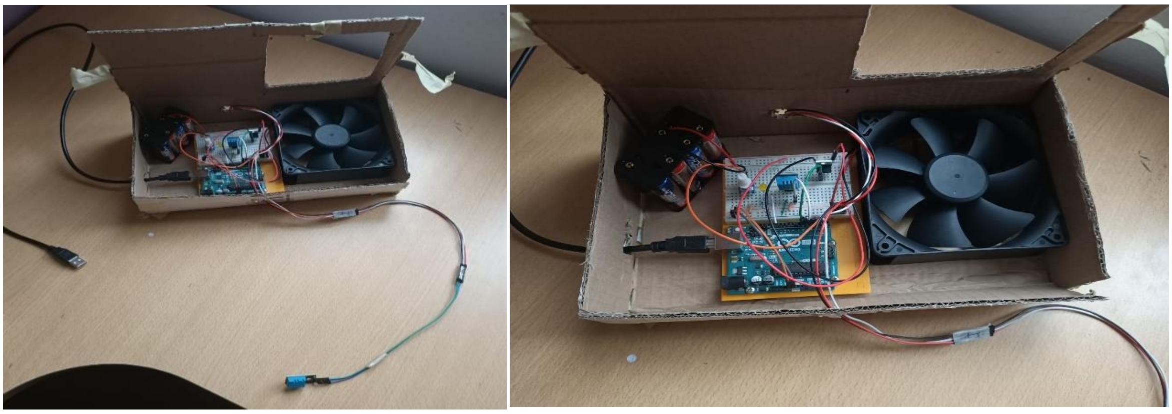


Fig.6 Prototype photo

6. Experiments

The goals of the experiments are:

- show that the physics model is correct and so our system is useful;
- find C_{on} and C_{off};
- show that the finalization algorithm is correct;
- show on a real test that our prototype behaves as expected.

We measured the time to dry two cloth soaked with 4g of water with different operating regime. Also, we want to observe the behaviour of humidity and temperature during time, so we used the program plx-daq to save the output of Arduino in an excel file. As said previously the clothes are dry when RHc<RHe+10.

In the following chart are reported the result

OPERATING REGIME	Fan always off q=0	2 min off 1 min on q=0,33	1 min off 1 min on q=0,5	2 min off 2 min on q=0,5	3 min off 3 min on q=0,5	2 min off 1 min on q=0,66	Fan always on q=1
TIME	113 min	48 min	33 min	38 min	32 min	30 min	21 min

So indeed, the drying system do his job and, by touching the clothes when the led light up, we observed that the finalization criteria is correct.

Of course, $T_{tot}(q)$ is affected by fluctuations, in fact the 3°,4° and 5° column should have the same value of T_{tot} but it is more or less the same with a mean of 34 min. This tells us that it does not matter the length of the period but only the value of q as predicted by the theory.

Since $\begin{cases} T_{tot}(q=0) = \frac{m_0}{C_{off}} \rightarrow C_{off} = 0{,}035\frac{g}{min} \\ T_{tot}(q=1) = \frac{m_0}{C_{on}} \rightarrow C_{on} = 0{,}2\frac{g}{min} \end{cases}$

with those value we can plot $T_{tot}(q)$

By plotting $T_{tot}(q)$ theoretical we can see that it fit the experimental data for q=0,33 q=0,5 and q=0,66, so indeed our model is correct.

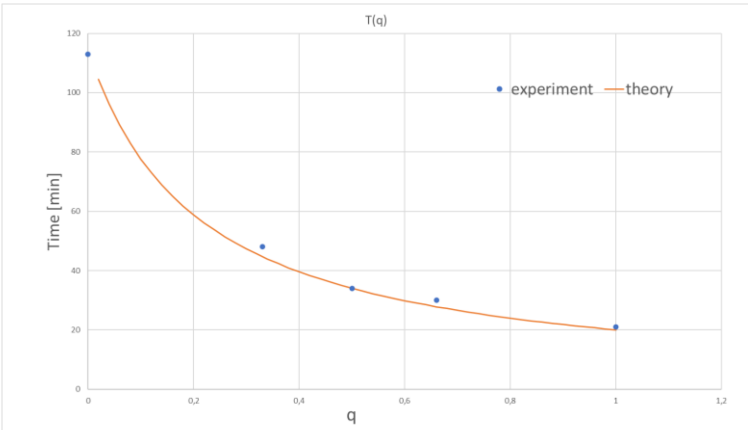
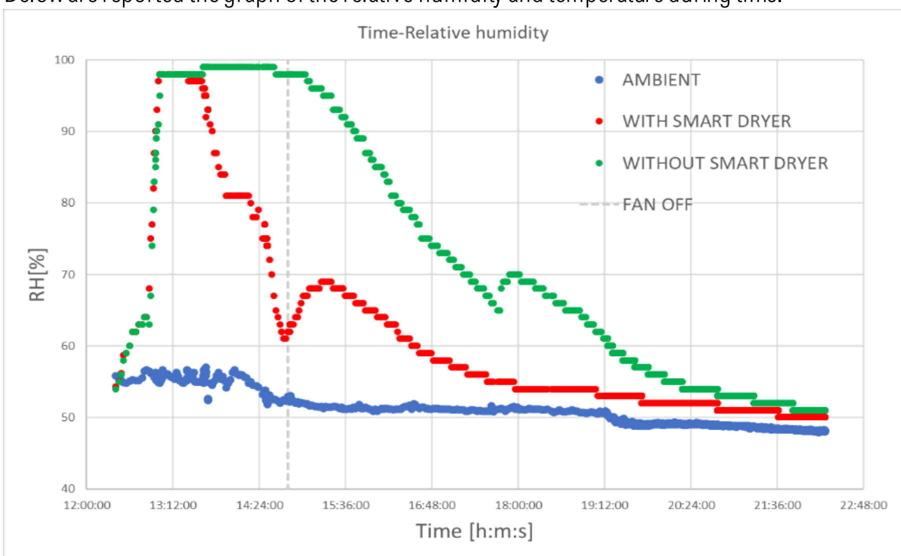


Fig.7 Comparison between experimental and theoretical results

Then we tried our system on a real case by comparing the drying of two very similar sweatpants on a full drying rack, one with our drying system (with the fan always on) and the other without, we used two external sensors in order to measure both and a third sensor to measure the ambient.
Below are reported the graph of the relative humidity and temperature during time.



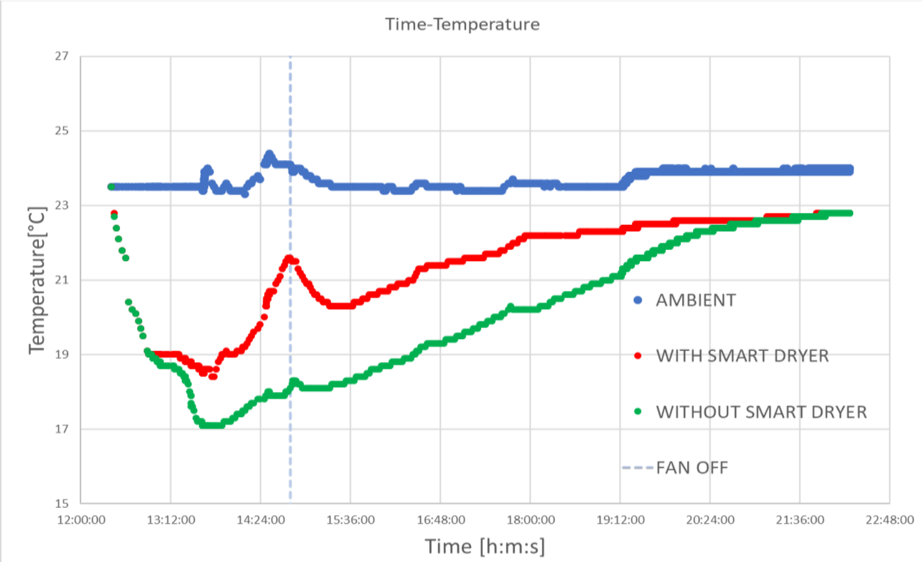


Fig.8 Humidity and temperature over time in the final test of the system

The clothes near smart dryer dried in 2 h and 22 min while the clothes without smart dryer dried in 6 h and 49 min. We can clearly see the effect of smart dryer on RH and T from the graph above: RH decrease faster and the temperature is higher.

7. Poll and Market Analysis

To understand the needs of the population when it comes to drying clothes, a survey of a sample of 85 people was carried out. It was thus possible to know the demand for the sample and evaluate the supply of our project accordingly. It was possible to understand if our project was going in the right direction, and possibly add/remove features that our project planned to have in the initial idea.

The decisive results of our survey are given below.

	Not much	Quite enough	A lot
How much is important that the clothes dry fast?	16,5%	47,1%	36,5%
How much is important that a drying system has little dimensions?	11,8%	60%	29,4%
How much is important that drying system is quiet?	3,5%	35,3	61,2%

Considering a drying system would you choose:	(1)	(2)
(1) Fast but expensive (2) Slow but cheap	23,5 %	76,5%
(1) Fast but with high consumption (2) Slow but with low consumption	9%	89,4%

The poll results suggest that the supply guaranteed by our drying system can meet the sample demand. And compete with our main competitor the automatic dryer. We want to highlight the characteristics of our system respect to a drying rack and a dryer with the following table:

	Drying Rack	Smart Dryer	Dryer
Price	20€	~40 €/module	800 €
Drying Time (with the same load)	8h	1.30 h	20 min
Size	167 x 56 x 92 cm	167 x 56 x 92 cm + Module Size 23 x 15 x 7 cm	80 x 60 x 60 cm
Consumption	0	0.01 kWh	60 kWh
Noise	0	48dB	65dB

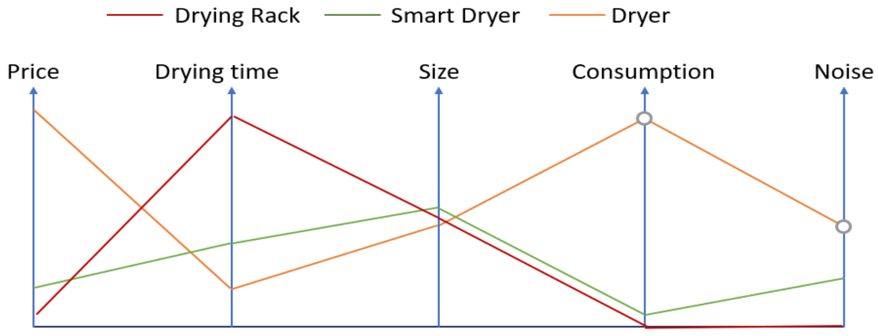


Fig.9 Comparison of the main characteristics of the drying systems

Overall, the curve that describes the smart dryer is located below the curve of the dryer, while comparing it with the drying rack, it is evident a considerable advantage on the drying time, which is one of the fundamental criteria for determining its efficiency.

8. Conclusion and further improvment

After an in-depth analysis of the drying systems available on the market and a study of their characteristics, it was possible to propose an alternative drying method capable of guaranteeing good efficiency but remaining economical and with low consumption. We would have like a lower cost per module, but since those are evaluation based on a prototype, we think that with a real stock production the price could be lower.

The system can be improved with a better physics analysis to choose the fan with the best drying time-power consumption ratio. Another improvement is considering the possibility to insert a motor to tilt the fan in order to cover a bigger portion of the rack.

9. References

[1] The physics of drying cloth, by Kaisa Bengtsson, Kathrine Segel, Henrietta Havsteen-Mikkelsen and Tim Padfield.

[2] Experimental Study of Drying Process of Porous Materials, Al-Madani, Ramadan, 2018/11/17