TREBALL DE FI DE GRAU: STRUCTURAL OPTIMIZATION FOR DEW-CONDENSERS USING COMPUTATIONAL FLUID DYNAMICS

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Abstract: *Water scarcity has been faced as one of the major threats to humankind this century. We here investigate a rather novel water collection device that wants to face this threat in an innovative form. We particularly find better geometries for the design of passive water collectors that take advantage of dew meteorological phenomena. We focus on the analysis of temperature distribution over a collection of dew-condenser surfaces by using Computational Fluid Dynamics. We detect key patterns for surface designs that maximize the cooling process by radiation while reducing heat transfer produced by convection. This is an especially innovative approach on air wells research field since the influence of geometries in the construction of condensers has had very little attention in the literature. The different geometries being tested allow us to clearly distinct between planar and funnel shapes in terms of efficiency. There are differences in temperature also between those geometries with folding on their faces and the ones without. Finally, we also evaluate the performance of the condensers in front of different wind directions. The findings from this highly multidisciplinary approach in collaboration with an architecture office will be useful for the construction of new dew-condensers in a near future.*

I. INTRODUCTION

Around 1.2 billion people, almost one-fifth of the world's population, lives in areas of water scarcity, and 500 million are approaching this situation. Another 1.6 billion people, almost one quarter of the world's population, face economic water shortage (where countries lack the necessary infrastructure to take water from rivers and aquifers) [1]. Water scarcity has been faced as one of the major threats to humankind this century [2]. The development of water resources for such areas is mainly centered on projects of large-scale and small-scale irrigation systems. However, these techniques are not following the line of a self-sufficient and sustainable societies promoted by several environmental and earth-friendly organizations and world-wide agencies.

Alternative methods for the collection of water have been studied. Devices to collect water from dew and fog have been somewhat successfully implemented, although there is still a long path to optimize and take the maximum profit from them. Experiments have proven that dew episodes in certain arid regions (as Morocco or Southern Spain) tend to be much more frequent than those of fog, and can correspond to almost 40% of the yearly rain contribution. For this reason, our effort is centered on dew episodes [2].

Dew phenomena had fascinated humanity for over 2,000 years, there are evidences on ancient and modern literature, poetry, folklore and in the Bible. Scientific interest in dew has had an equally long story [3]. The publications by Monteith [4] [5] can be considered as a marker in dew research, he saw the necessity of highlighting some dew fallacies to the scientific community, and worked towards understanding energy and heat balance mechanisms of dew formation and evaporation.

An example of dew collection is found in Lanzarote (Canary islands), where traditionally, they use funnel shaped holes on their volcanic sand to feed their vines for wine production without any rain episode. The first massive dew collectors built in France in the first quarter of the 20th century gave very low yields [6] [7]. They both followed a passive collector constructed by Zibols in Crimea (Ukraine) in 1912, which is based in a pyramid-shaped passive dew-condenser [8] whose collected yield was much less than the calculated for the original structures, but still a noticeable amount. Over the last decade, passive dew collectors have been built using materials that can enhance radiative cooling and thus improve dew collection output [9] [10] [11]. More recently, a significant yield was obtained by Nilsson [12] while using a small condenser made with a special foil design to benefit from the radiative cooling. The following condensers were designed and built aiming to induce and increase the radiative energy exchange. On 1999, OPUR (International Organization for Dew Utilization) was founded to explore and develop those condensers as a new inexpensive and practical alternative water source. Nowadays this organization is supporting many international scientists in their tasks on scientific and technical research on dew collection [13].

For the purposes of condenser optimization, meteorological conditions such as air temperature, air humidity and sky radiation are imposed by the geographic and climatologic location of each device [14]. But in order to increase the yield of dew harvesting, it is possible to maximize the long wave-length emitting material properties of the condensing surface (near infra-red) or minimize the short wavelength absorption (sun visible light). It is indeed possible through the device geometry lower the wind velocity on the condensing surface, increase sky radiation exposure or recover most of the water drops [15].

In this study we will focus on the optimization through several geometries, without going much deeper on material properties that optimize radiation exchange, and by keeping a certain fixed values for the environmental conditions. We sort the geometries by their cooling capacity mostly reflecting the reduction of wind velocity on the condensing surface. Computer Fluid Dynamics (CFD) is the approach chosen for this purpose. The study leads to a quite unexplored path on dew-condensers design, as the best known and most used geometries on the recent studies are mainly planar shapes with a certain slope (30 degrees). New and completely different shapes (from funnels to folded geometries) are tested to compare and focus on the ones with lower surface temperatures.

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There is a wide range of disciplines involved in understanding and optimizing dew collection within the construction of condensers. From the physics of phase transitions to the design and architecture of geometries to collect water, we went through transport phenomena and micrometeorology aspects in order to achieve this multidisciplinary study aimed to construct efficient dew-condensers.

The research is part of a larger collaboration with Appareil, an architecture office, through an agreement of the École Spéciale d'Architecture from Paris. The collaboration aims to develope and understand the science behind dew-condensers. Appareil has,supported the current study by providing novel geometries and contributed in the discussion for finding these geometries jointly with Marc Carratalà, an Environmental Engineer whose work has been more focused on materials and isolation choices, as well as experimental set up which goes far beyond the current paper goal. All geometries proposed are in any case plausible for architecture purposes.

II. THEORETICAL BACKGROUND

A. DEW FORMATION

Dew phenomena is a condensation process in nature, where the water molecules goes through a phase transition from vapor state in air to liquid over a surface. This transition takes place on the surfaces where the temperature is lower than ambient, and this translates into a change of state.

The most essential variables on dew formation are temperature and humidity. Both variables are related with the dew point temperature by the psychometric chart given by Fig. 1. We want to focus on the temperature, which is a measure of the average random kinetic energy of the molecules in a substance, so it will be the observable condition on energy exchange [16]. In order to force water condensation from air on a surface, the first step will be to obtain a right temperature distribution, below the dew point temperature.

There are four modes of heat transfer: convection, conduction, radiative exchange and latent heat transfer. Since heat transfer in air is mainly by convection, or transport of "blobs" of hot/cold air, we may expect the temperature at any point of the air to be slightly different from the one measured by the thermometer. So there are fluctuations on the air temperature of around 1ºC.

Humidity: When the dew water drops to the dew point, the latent heat of condensation that is added to the air prevents it to drop much below. Saturation vapor density established when the number of particles escaping from the liquid is equal to the number of particles being recaptured by the liquid.

The dew point temperature is the T at which air, when cooled without changing its water content, just saturates.

Radiative exchange: If there is a body with infinite number of transitions spaced throughout the electromagnetic spectrum, this medium would absorb all the radiation falling upon it and will radiate the maximum amount of energy that it would be capable to radiate at its own temperature. We call that a "blackbody".

Simplified psychometric chart.

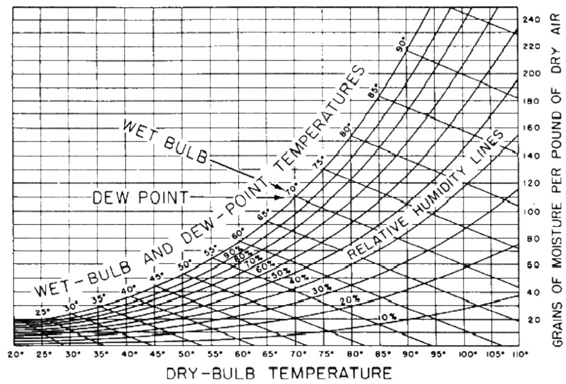

FIG. 1: Psychometric chart, it establishes the relation between ambient temperature, humidity and dew point.

The radiant emmitance of a blackbody is described by Steffan-Boltzmann law

$$\phi_b = \sigma T^4. \quad (1)$$

Long wave irradiance from the atmosphere can be determined by $\Phi=\varepsilon\sigma T^4$, if we know the value of clear sky emissivity.

For our CFD simulations, we supposed a sky emissivity constant and equal to 1. For the sky temperature, it was determined according to the Josey [17] formula with a relative humidity of 90%:

$$T_{sky} = T_{air} + 10.77n^2 + 2.34n - 18.44 + 0.84(T_{dew} - T_{air} + 4.01). \quad (2)$$

Heat transfer: There are two main mechanisms for heat transfer in our study; diffusion and convection. By diffusion the heat and mass is transported in still air or water. It is also important in convective heat and mass transfer between surfaces and fluid flowing over them since a thin boundary layer is formed near the surface through which transport is by diffusion.

For convection, we will use Reynolds's Number, to characterize the flow that is being studied. That is:

$$Re = ud/\nu, \quad (3)$$

where u is the fluid velocity, d is the characteristic dimension and ν is the kinematic viscosity. At low Reynolds (under 5E+04) viscous forces predominate and the flow is laminar. While for high Reynolds inertial forces predominate and the flow becomes turbulent. In our we can consider the flow with the laminar approach on the surface.

Free convection takes place whenever a body at one temperature is places in a fluid at lower/higher temperature. In order to know if we are dealing with free or forced convection we'll need to calculate the ratio

$$\frac{Gr}{Re^2} = agd\,\frac{(Ts-Ta)}{u}, \quad (4)$$

where a is the coefficient of thermal expansion, (1/273 for air), g is the gravitational acceleration, d is the characteristic dimension, and u is the fluid velocity.

If it is smaller than 1, which is our situation, then forced convection dominates over natural convection.

In terms of convective heat transfer, the program needs the input of a certain coefficient h. This coefficient comes from de Newton's law

$$Q = hA(Ts - Tf), \quad (5)$$

and has units W/m^2. It is a simplified correlation between the fluid state and the flux conditions. There are some fixed values for h already tabulated depending on the media and type of flux. For our case, we are dealing with low forced

Convection, so we use a value of h=20 (h air is between 5-25 for natural convection).

B. COMPUTATIONAL FLUID DYNAMICS

COMSOL Multiphysics® is a licensed powerful integrated user interface environment designed for cross-disciplinary product development with a unified workflow for electrical, mechanical, fluid, and chemical applications. It is a general-purpose software platform, based on advanced numerical methods, for modeling and simulating physics-based problems. It allows the users to work with coupled or multiphysics phenomena [18].

We used the Universitat de Barcelona license and the computational resources from Physics Faculty and Departament de Física Fonamental to run the Computer Fluid Dynamics simulations.

We used the heat transfer branch, as the main aim is to define a surface map of temperatures for each condenser. So we chose the "Conjugate Heat Transfer", which is a version of the Laminar Flow interface in a 3 dimensional space. The conjugate Heat transfer branch is a predefined multiphysics coupling consisting of a single-phase flow interface, using a compressible formulation, in combination with a Heat Transfer Interface. In our work, we will use laminar and stationary conditions, as we are supposing that the condenser will have enough time during the night to achieve that condition.

The geometry consisted in a cube (3x3x2m^3) filled with air, and on its basis, we placed the condenser surface (1m long). Condenser's geometry was built by keeping its surface in contact with the internal space the box, and centered conserving the same distance to any of the cube faces. The condenser surface material is polyethylene. The different geometries tested can be observed on Fig. 2.

After several experimental tests with different materials to evaluate their performance in terms of drop formation and channeling, as well as their malleability and resistance properties involved on the construction process, we decided that this certain plastic would be the best and most affordable option.

The boundary conditions for the problem were:

Initial Values: initial velocity field, pressure and temperature. We used Normal Conditions for Pressure in all our experiments (1atm), and the ambient temperature was 288K (15ºC) according to the average night temperature during summer months on our meteorological station (Pujalt, Spain). For the velocity field, we kept a wind intensity of 1.5m/s (in order to observe the convection and radiation cooling effects on the surface), but we changed the direction in order to test the effect on the temperature surfaces

Fluid: the air contained inside the boundaries of our simulation needs to be defined as a gas state that can flow from an inlet boundary to an outlet, and create an inside current. The air specific parameters define a temperature and velocity gradient among the volume.

Surface to Ambient Radiation: one of the most interesting cooling effects that we want to observe relays on the radiation from the condenser to space, as well as the opposite direction. So we need to define the condenser surface as a radiative body that will emit energy according to the Stephan-Boltzmann Law for a black body. With a sky temperature 271K (-2ºC). The sky temperature was determined according to the Josey formula, with a relative humidity of 80% and a sky emissivity constant and equal to 1. Emissivity is a material parameter that needs to be specified too, is the relative ability of its surface to emit energy by radiation. This value depends on the surface properties such as color or thickness, for polyethylene black plastic the theoretical emissivity is 0.92.

Convective cooling: the other cooling process on the condenser surface is convection, which is due to the wind and air contact with the surface. The equation used to determine the temperature depends mainly on the External/Ambient temperature and the heat transfer coefficient, as well as on the condenser geometry. That is:

$$-n \cdot (-k\nabla T) = h(T_{ext}^4 - T^4). \qquad (6)$$

On this equation h is the convective heat transfer coefficient that depends on the type of media, gas or liquid, the flow properties such as velocity, viscosity and other flow and temperature dependent properties. [i]

The convective heat transfer coefficient of air is approximately

$$-h = 10.45 - v + 10v, \qquad (7)$$

where v is the relative speed of the object through the air.

Inlet & Outlet: to include an air flow inside our volume we need to define an inlet and outlet boundaries for the air. Depending on the wind direction that we wanted to test, we selected one face or another of the geometry. The wind intensity is kept constant (1.5m/s) and we supposed a laminar flow due to the weak current intensity.

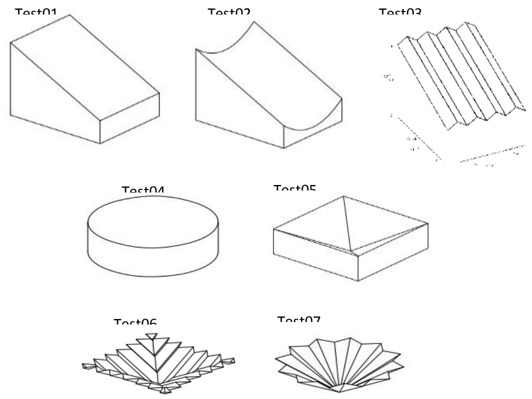

FIG. 2: Geometries tested with Computational Fluid Dynamics.

Finally, we need to create a mesh in order to run the numerical calculations. We adapted a non-homogeneous and well-distributed mesh depending on the particular characteristics and requirements of each geometry. A thinner mesh was made for the condenser surface, while a coarser one was kept for the rest of the geometry.

III. RESULTS

Figure 3 resumes the results obtained for each geometry under the same external conditions showing of the differences between them in terms of temperature distribution over the surfaces.

In order to evaluate and compare the performance of the different tests, we use the cooling efficiency term

$$\Delta T = \frac{(T_C - T_A)}{(T_{ref} - T_A)}, \qquad (8)$$

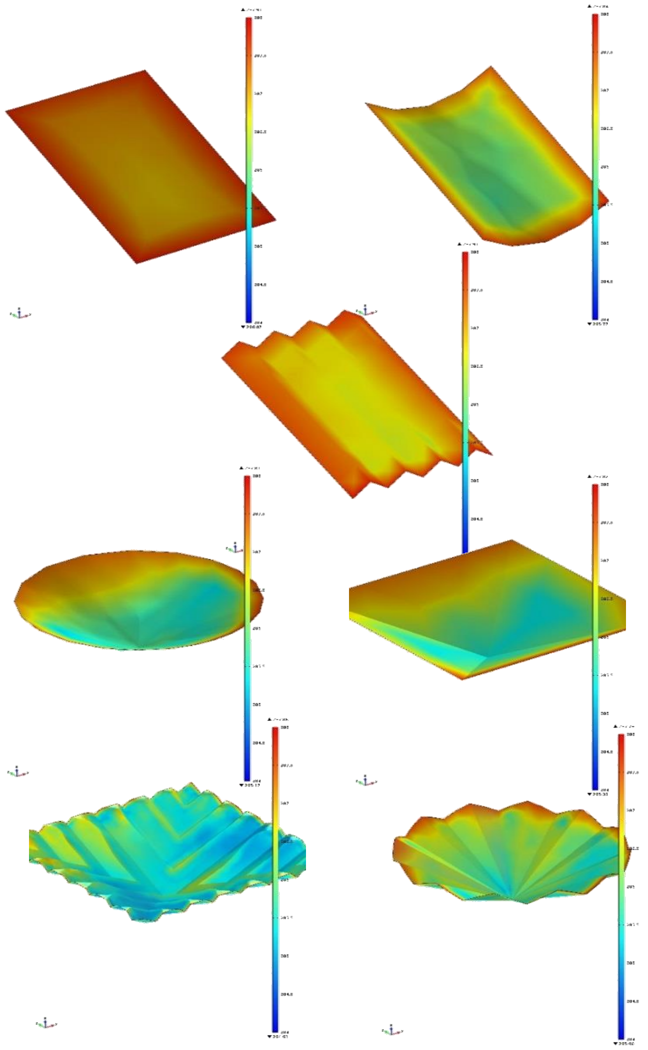

FIG. 3: Temperature distributions over the different geometries as a result of radiation and convection energy exchange

used priory in other studies about radiation-cooled dew-condensers using computational fluid dynamics [19], where T_C is the average temperature achieved by each condenser, T_A is the ambient temperature (288K/15ºC) and T_{ref} is the average temperature of the condenser chosen as a reference. In our study we have chosen the planar condenser 30 degrees inclined, because it is the geometry more commonly used on prior studies about dew-condensers, and the one we would like to optimize. The results for our condensers are given on Tab. 1.

It is clearly observed that the funnel shaped geometries have cooler surfaces than the planar ones. The geometries with folded surfaces (test03, test06 and test07) also present a higher cooling efficiency than their flat respective ones.

In terms of dew, for the conditions imposed on the simulations (T_{amb}=15ºC h=90%) the Dew temperature is T_{dew}=13,6ºC.

Under these ideal conditions, only the funnel shaped condensers will achieve average temperatures under the dew point. Although the rest of geometries do not have their average temperature below T_{dew}, they may be able to achieve lower temperatures at some specific points on the surface, where dew could also condense. But in order to obtain a greater amount of dew, the average temperature must be below the dew point. We should keep in mind that small changes around the conditions used for the simulations will not affect the order of efficiencies found for the condensers.

In order to give a notion of the temperature dispersion over the surface the standard deviation of each geometry was used as the indicator. This values were obtained by using the software tools to integrate the equation and thus obtain

$$\sigma = \sqrt{\int (T - T_{ave})^2 dT}, \qquad (9)$$

In order to compare between the geometries, standard deviations will be normalized over the value for test01 as shown in Tab. 1. In terms of standard deviation, the greater this value, the more homogenous the distribution will be around the main temperature.

For each geometry, the dependence with wind direction is also tested. Wind is the principal cause origin of heat on the surface, and we are trying to minimize its effect and find a geometry that does not depend on its orientation. For functional reasons, the condensers should be as much independent of wind as possible. We tested three different directions; frontal, lateral and backward. For wind dependence estimation we define

$$\Delta w = 100 \frac{|(T_{max} - T_{min})|}{T_{ave}} \qquad (10)$$

where T_{max}-T_{min} is the difference between the maximum and minimum average temperatures achieved for a single geometry under the three different wind conditions. And T_{ave} is the average temperature for those three cases. The resulting wind dependence is shown in Tab. 3.

From the chart we can see that the geometries less affected by the wind direction are the funnel shaped, as one could expect, while the planar ones present change on their temperature distribution depending upon the wind.

Among the funnel shaped condensers, we can also observe a significant variation on variance for the folded and non-folded geometries, with a clear advantage on the former ones.

name	efficiency	deviation	Δw(%)
test01	1.00	1.0	5.00
test02	1.09	1.2	7.05
test03	1.35	1.5	5.22
test04	2.44	2.8	1.50
test05	2.31	3.1	1.17
test06	3.38	3.6	0.14
test07	2.80	2.9	0.04

TABLE. 1: C1: the efficiencies obtained for each geometry, using the test01 as a reference. C2: standard deviations obtained for each geometry, normalized by test01. C3: wind dependence for each geometry.

IV. CONCLUSIONS

After testing the cooling efficiency of 7 different geometries by using CFD, the results show that in terms of the main condenser structure, the most efficient ones are the funnel shaped with more than 3 degrees of difference with ambient temperature. These geometries are particularly interesting also for their symmetry, which makes them independent of wind direction. And also because they had never been tested in prior studies in the literature. The methodology been applied and the multidisciplinary approach with architects has led to these innovative forms.

The results can be explained when looking at the wind velocities and trajectories over the condenser surface. For the planar geometries the wind (hotter than the surface due to radiation exchange), uses to impact directly on the surface, consequently heating that part. While on the funnel shaped geometries the wind gets cooled from its initial temperature when it impacts to the surface. The change on its temperature leads on cooled air that slips from the upper parts of the folds to the valley, and due to its initial momentum it moves up again, creating a turbulence at the center of the surface that translates into a lower temperature distribution by reducing the convective heat transfer effect.

Temperature dispersion over the surfaces also presents optimal results on the funnel shaped geometries. It indicates than other than a low main temperature, the distribution will be close to that value on many regions of the surface, which is positive, because in order to be a good condenser the temperature may be as much extended as possible below the dew point.

After these results, we can suggest a further investigation on temperature distribution by using CFD on new geometries. It could be of great interest to design new geometries based on the funnel shaped and folded properties, by keeping in mind the architecture approach in terms of finding feasible and constructive shapes.

Although the temperature is the main indicator for water phase transition, we need to recall that for dew collection there is another main property that needs to be analyzed; i.e. drop formation. The geometries with the best temperature distribution over their surface will then need to be tested in order to ensure efficient water collection. Experimental tests will have to be done in a future along these lines, which in parallel with the computer simulations would allow us to better select the geometry for new dew-condensers. Some experimental models based on current geometries herein studied have been already set on Pujalt's Meteorological station. We expect to obtain experimental valuable results to validate current computer simulation during the following months.

V. APPENDIX

You can find attached each one of the simulation tests with their corresponding data, images and a brief explanation.

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