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A THERMODYNAMIC APPLICATION TO ANALYSE THE FLOW FIELD IN AIR

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ABSTRACT

The thermodynamic effect of a density gradient in a colder fluid as a result of a hotter plate located below it is something that is well known. However, its use as a flow field indicator using a light coil shaped body is a recent application developed by the author of this paper. The paper contributes to bring ahead this concept by a parametrical experimental analysis aimed at assessing the relationship among three of the parameters that mainly influence the whole process: the angular velocity of the coil as a dependent variable; the number of turns in the coil as the first independent variable and the weight of the coil as the second independent variable. A suitable apparatus was realized. The tests performed showed that, apart from a very few cases, an increase in the number of turns produces an increase in the angular velocity of the coil. A particular behaviour is observed for the weight of the coil: an increase in weight augments the angular velocity for small values, while for larger values the trend is opposite. Some considerations about the rotational stability can explain the entire concept, although further research will help deepen our knowledge of the process for wider parametrical ranges.

Keywords: coil, density gradient, flow field, number of turns, rotation, thermodynamics.

1 INTRODUCTION

A very common problem that we often face in thermodynamics and thermal fluid dynamics, when studying natural systems, is that of acquiring a certain degree of knowledge about the flow field of a cold fluid that is stationary at the beginning of the process and is in contact with a hot body or surface. This, in fact, induces a process of internal buoyancy in the fluid, as a result of the density gradient that develops [1], which leads to a flow field status that has very seldom been studied experimentally, as the scientific literature reports. Research has instead mainly focused on the heat removal associated with this phenomenon, in the case of both vertical [2, 3] and horizontal hot surfaces [4, 5], in terms of optimizing the geometries involved in enhancing the heat exchange, generally with special attention to the coefficient of heat transfer or to its dimensionless equivalent—the Nusselt number. However, there is very little information concerning the flow field. This scarcity of knowledge fundamentally arises from the fact that any instrumentation aimed at measuring the flow patterns inside a fluid causes a not easy to define disturbance in the flow field itself, which can also strongly affect the measurement taken. This is very true in cases similar to those specified above, where mapping the flow field so as to give the experimental study a statistical relevance would imply such a high number of sensors that the pressure losses determined in the fluid would severely affect the results obtained and also the general validity of the investigation performed. Thus, from an experimental point of view it is evident that it is very hard to define a general criterion to fully investigate the flow field of a system composed of a hot surface in contact with a cold fluid. However, in three recent publications, Lorenzini [6, 7, 8] first proposed and then tested in a few cases a practical criterion that allows for a partial solution of how to investigate experimentally the flow field in the case of a horizontal plane hot plate over which colder air is present, being stationary initially. The criterion is based on the fact that the temperature gradient that develops over the plate generates in the air a force directed upwards which is able to induce a rotation around a vertical rod of a light coil-shaped body hanging over the rod itself. The angular velocity of the coil can be affected by the many thermodynamic and geometrical parameters involved in the system such as the plate temperature, the air temperature, the coil weight, the number of turns, the turn width and the slope between one turn and another. In this sense, the rotation of the

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coil gives some indirect information about the flow field in the air as modified by the heat flux due to the hot plate and because of this it can be regarded as a tracer of the velocity field. The phenomenon described here has evident connections to some movements occurring in nature, such as tree leaves in an updraft and leaves falling helicoidally to the ground—all of these processes can be clearly described by means of Bejan's Constructal Theory [9], which is becoming ever more essential in the description of natural events. This paper, following the papers quoted above by the author of this paper, presents the results of an experimental investigation aimed at assessing how the angular velocity ω (in rad s^{-1}) of the coil is affected by the number of turns N of the coil, also in relation to the other influential parameters just mentioned.

2 EXPERIMENTAL SET-UP AND TESTS PERFORMED

The thermodynamic phenomenon outlined in the previous section, and used in the present research as a tracer of the flow field in air, causes, for its own nature, the non-scalability of the process, as different dimensions of the apparatus do not enhance/diminish the consequent motive effect but only the weight of the coil, which could dramatically increase the inertia in the contact coil rod tip [8]. This consideration has led to the experimental apparatus being designed again for light coils, as this choice acts in the sense of reducing any frictional resistance at the tip to a limited value, which has not been calculated due to the fundamentally qualitative aims of this research. Moreover, other variables such as viscous, pressure and inertial fluid forces affect the process, but these variables, which are not at all negligible, are to be considered in a future study. At the present stage of the research, these variables are taken into account just as a part of a qualitative phenomenon and not as single contributions, which future studies will have to assess. Two other relevant fundamental parameters to be kept in mind are the general shape and the unsteadiness of the convection plume that are believed to be the actual cause of the phenomenon observed here and are consequently directly quantified by all the results reported in the next section of this paper. An essential schematic illustration of the set-up is shown in Fig. 1: a horizontal stainless steel parallelepiped plate is uniformly heated from below by four electrical resistances each characterized by a rated power of 500 W, and all of them are fed by a Variac transformer. The middle of the plate holds a slender vertical stainless steel rod with a sharp tip, over which the light coil is hanging in a balanced position: the upper part of the coil participates to the coupling, which is covered by a layer of Teflon so as to reduce the friction as far as possible. The rod has a uniform cross-sectional diameter of 2 mm, whereas its length changes depending on the coil dimensions used in order to keep the small distance between the coil and the plate equal to 60 mm and not to change the force acting upon the coil itself.

The plate has squared bases with a side Q of 350 mm and thickness W of 30 mm: these dimensions allow one to neglect any central consequences of the checkerboard effect. During the tests the plate is insulated, except its upper surface, by means of layers of expanded polyurethane 20 mm thick. The centre of the plate, which holds the rod, has a 15 mm deep hole with a diameter of 2 mm. The top of the coil, which is in contact with the rod tip, is circular with a diameter of 30 mm. As the coil is conical, at each turn the diameter varies by a factor of $2L$ and so D (see Fig. 2.1) is not constant. The number of turns N and the turn width L (in mm) depend on the test made and consequently the height H and the weight P of the coil as well. As regards the weight, two coils with the same shape characteristics can have different weights by adding/eliminating an aluminium tape, dense and slender, which allowed to vary the weight without causing major changes to the aerodynamics of the process. Figure 2 shows the details of the apparatus in case of a coil with two turns. As seen in the figure, the plate temperature is measured by two digital thermometers with a mean margin of error equal to 0.5% in the temperature range between 30°C and 120°C, according to the manufacturer, which means that each temperature value measured, lying within that range, could be shifted by

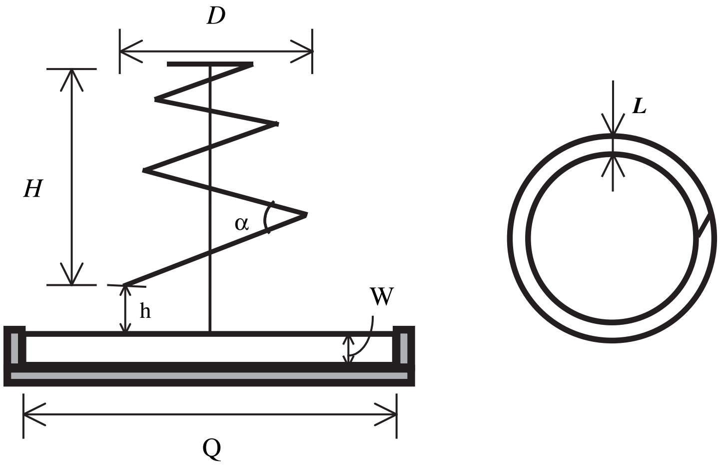

Figure 1: Schematic illustration of the experimental apparatus (left) and a single turn (right).

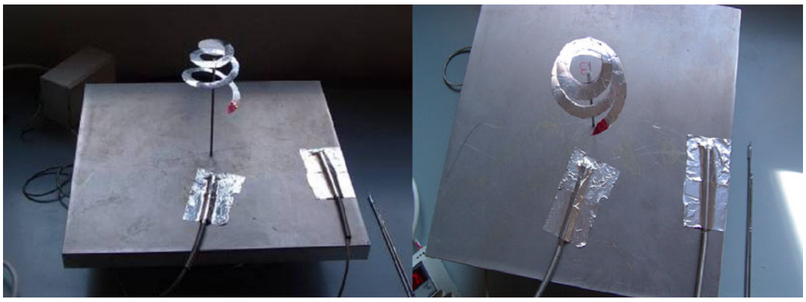

Figure 2: A coil with two turns, thermometric probes and no thermal insulation.

0.5% from its true value. No calibration was required for the thermometer due to its own internal calibration. Moreover, there was no need for thermocouples as the tests were not focusing on the transient state but just on the steady-state measurements.

3 TESTS PERFORMED AND THE RESULTS OBTAINED

The present study is mainly aimed at analysing the dependence of the angular velocity ω of the coil on the number of turns N which the coil is composed of, also taking into account the plate temperature T_p (in °C) as well, which is probably the most influential parameter, as further research in due course seem to confirm. In particular, N assumes the values 2, 3 and 4; the plate temperature T_p ranges from 65.0°C to 85.0°C in steps of 5.0°C: these values, together with that of the air temperature mentioned immediately below, give a Rayleigh number range between $Ra = 3.56 \times 10^{-6}$ (for $T_\mathrm{p} = 65°\mathrm{C}$) and $Ra = 5.03 \times 10^{-6}$ (for $T_\mathrm{p} = 85°\mathrm{C}$). This confirms that the field of investigation fully pertains to a natural convection context. The other variables that are considered to influence the phenomenon are kept constant during these tests and are varied only in different tests to monitor qualitatively their effect on the main trend. Among the other variables, the surrounding air temperature T_a (in °C) is kept constant at 21°C during the entire process using an environmental thermostat; the slope α (in radian) between one turn and another is always kept equal to ($\pi/6$) rad; the width of a turn L was assigned the values 10 and 20 mm; the weight of the coil P (in grams) ranged between 1.0 and 6.0 g in steps of 1.0 g. The values of the plate temperature chosen were based on a preliminary experiment, which proved that the highest triggering temperature, i.e. the temperature that allows for a stable and repeatable rotation of the coil, for the geometrical configurations used in experiment was equal to 64.0°C. Moreover, the steps of 5.0°C help in reducing the risk of data superimposition due to the experimental error. Again, the experimental error was reduced as much as possible by acquiring not just single experimental data for the angular velocity ω of the coil but the statistical means of 15 repetitions for each single test, assuming the 'true' value to be the mean of the 13 intermediate values after discarding the highest and the lowest values. Each test consisted of recording the time necessary for a coil to rotate 30 times around the rod: this analysis was aided by a digital camcorder.

Among the results obtained, those with a stronger statistical relevance and that are more characteristic of the trends of the phenomenon being analysed are reported in Tables 1 and 2. At a first glance,

Table 1: Variation of the angular velocity (in rad s^{-1}) with the coil weight P (in grams) and the number of turns N at a turn width $L = 10$ mm and different plate temperatures.

	ω (rad s^{-1})		
P (g)	$N = 2$	$N = 3$	$N = 4$
(a) $T_p = 65$°C			
1.0	1.40	1.97	–
2.0	1.43	2.05	3.53
3.0	1.52	2.92	3.71
4.0	2.19	2.96	3.88
(b) $T_p = 70$°C			
1.0	1.72	3.03	–
2.0	1.84	1.78	3.64
3.0	2.11	3.49	4.81
4.0	2.35	3.87	4.95
(c) $T_p = 75$°C			
1.0	2.09	3.56	–
2.0	2.21	3.80	5.00
3.0	2.29	3.93	5.27
4.0	2.71	4.40	5.55
(d) $T_p = 80$°C			
1.0	2.11	3.83	–
2.0	2.43	4.12	5.46
3.0	2.40	4.37	5.59
4.0	2.64	4.75	6.04
(e) $T_p = 85$°C			
1.0	2.32	2.09	–
2.0	2.58	4.62	5.87
3.0	2.79	4.76	6.01
4.0	2.95	4.87	6.18

the data show that the angular velocity ω of the coil is affected by the number of turns N, keeping all the other influential parameters constant, in the sense that the higher the latter the more elevated the former. Even if the research requires further investigations on this parametrical dependence, thereby widening the range of values in the analysis and the geometrical configurations tested, an interpretation of this first result can also be attempted aided by a direct and critical observation of the process. In fact, when the number of turns is higher, the small vibrations and oscillations, resulting from the buoyancy induced by the hot plate and acting on the coil, are distributed on a wider surface therefore

Table 2: Variation of the angular velocity (in rad s^{-1}) with the coil weight P (in grams) and the number of turns N at a turn width $L = 20\,\mathrm{mm}$ and different plate temperatures.

	ω (rad s^{-1})		
P (g)	$N = 2$	$N = 3$	$N = 4$
(a) $T_\mathrm{p} = 65°\mathrm{C}$			
2.0	1.54	2.15	3.88
3.0	1.60	3.23	4.41
4.0	2.34	4.94	6.74
5.0	2.11	4.39	6.61
6.0	2.05	3.99	6.57
(b) $T_\mathrm{p} = 70°C$			
2.0	1.99	3.46	4.78
3.0	2.23	3.54	5.09
4.0	2.46	4.85	6.92
5.0	2.20	4.61	6.87
6.0	2.11	4.33	6.69
(c) $T_\mathrm{p} = 75°\mathrm{C}$			
2.0	2.26	2.05	5.05
3.0	2.42	3.94	5.75
4.0	2.83	5.02	7.06
5.0	2.51	5.30	6.98
6.0	2.44	4.97	6.82
(d) $T_\mathrm{p} = 80°\mathrm{C}$			
2.0	2.50	4.78	5.87
3.0	2.53	5.61	6.04
4.0	2.71	5.65	7.31
5.0	2.16	5.43	7.23
6.0	2.16	4.99	7.07
(e) $T_\mathrm{p} = 85°\mathrm{C}$			
2.0	2.96	5.03	6.16
3.0	2.99	5.84	6.99
4.0	3.02	6.34	7.83
5.0	2.29	6.30	7.60
6.0	2.13	5.96	7.15

allowing for a more regular and better distributed revolution of the coil itself around the rod. As evident from the data set the trend highlighted holds particularly true for higher plate temperatures and higher coil weights, which confirms the interpretation provided, as both are typical conditions at which the disturbances to the rotation of the coil would become more relevant to the final result: a higher plate temperature enhances the buoyancy in the air and also the forces directed upwards and acting on the coil, and this contributes to a more relevant risk of vibrations and oscillations to the structure. This item also has a direct link with the shape and the unsteadiness of the convection plume, both playing a relevant role in the process, as previously explained. Recollecting that the centrifugal force is directly proportional to the weight of the system involved, it can be proved that enhancing the weight of the rotating coil in the presence of an 'irregular' plume contributes to a shift of the trajectory from its regular circular shape. As already discussed elsewhere by Lorenzini [8], the effect of the plate temperature T_p on the process is evident: high plate temperatures result in high angular velocities.

A closer examination of the tables shows that the trend does not hold true for all the cases considered as some of data pertaining to coils characterized by a small weight, with respect to the range examined, show an inverse the trend and a reduction in the angular velocity with the number of turns. This singularity is in fact believed not to have a proper meaning linked to the nature of the phenomenon being analysed here but to be just due to the fact that the revolution of lighter coils around the rod is relatively more affected by the air friction than the revolution of heavier ones. Nevertheless, this hypothesis will require a deeper analysis in the future in order to improve the knowledge related to the aerodynamics of the process and in particular to the rotational equilibrium of the coil as associated with the air friction.

4 CONCLUDING REMARKS

The problem of studying the flow field in the air over a hot horizontal plate by experimental means has been scarcely discussed in the literature. This paper deals with this task using the tracer function of a light coil, as previous research by the same author proved possible [6, 7, 8], which rotates around a vertical rod as a result of the density gradient due to the heat flux from the plate. The first part of the research involved the realization of a suitable experimental set-up. Among the possible parametrical investigations of the many parameters that influence the rotation of the coil, the most significant experimental results related to the variation of the angular velocity ω of the coil with the number of turns N are reported here. The weight of the coil P is also analysed as a major influencing factor, while the other variables, such as the turn width L and the plate temperature T_p, are kept constant in each test and varied only from test to test. The slope α between one turn and another was instead always constant and equal to $(\pi/6)$ rad as is the air temperature T_a, maintained at a value of 21°C by a thermostat. The results showed that the higher the number of turns N, the higher is the angular velocity ω of the coil apart from a very reduced set of tests, all of which are nevertheless characterized by a low weight of the coil P. The weight is in fact associated with the stability in rotation of the coil: when P is very small (up to 4.0 g) the rotation is less stable and then an increase in P augments ω because it contributes to the equilibrium of the process; for bigger weights (up to 6.0 g, the upper limit of the weight range analysed here) the opposite trend is exhibited. This means that small weights are more likely to be associated with singularities in the angular velocity trend. Further research will have to be carried out to deepen our understanding of the relationship between ω and N for wider ranges of parameters by also investigating the possible mutual interactions among the other influencing parameters and looking for possible non-linear relationships between them. At present, no comparison can be made between the results obtained by this technique and other authors' results as the present method is only an indicator of the general state of the flow field and cannot provide precise data because of the stiffness of the coil which does not allow any differential rotation.

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NOMENCLATURE

D	outer diameter of the coil (in mm)
h	minimum distance between the coil and the plate (in mm)
H	total height of the coil (in mm)
L	turn width (in mm)
N	number of turns
P	coil weight (in grams)
Q	aluminium plate side (in mm)
T_a	air temperature (in °C)
T_p	plate temperature (in °C)
W	aluminium plate thickness (in mm)
α	slope between two adjacent turns (in radian)
ω	angular velocity (in rad s^{-1})

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