FROM SHAPE AND TEMPERATURE TO ENERGY CONVERSION ANALYSIS: A CASE STUDY

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ABSTRACT

The experimental research here presented is aimed at describing some aspects of a process of energy conversion, from thermal to mechanical.

This conversion, induced by a hot plate over which a light coil is free to rotate as a consequence of the temperature gradient determined in the fluid medium, is then used as an indicator to acquire some knowledge about the flow field in the fluid itself.

The results obtained are not only affected by the thermal fluid dynamic conditions of the whole system but also by the tracer utilised, that is the light coil, with its shape and its properties.

Among them the weight, the effect of which on the angular velocity induced in the coil is here investigated by means of an experimental setup.

The results, requesting a dualistic interpretation, show that the influence of the weight has to be considered together with a rotational stability analysis. Further research is in progress.

1. INTRODUCTION

Energy is in many senses one of the major issues that the present era is facing. This does not hold true just for what relates to its supplying or management, but also for all the problems concerning its conversion from one form to another, which in nature and in the technical practice often happens in many ways. The present paper is aimed at treating specifically of a case study in which thermal energy is partially converted in mechanical energy as explainable by a direct application of the basic principles of heat transfer in natural circulation: a hot plane plate put in contact with a colder fluid, initially stationary, is subjected to a thermal stratification and subsequently to a density gradient [1]. The system/process here outlined very generically has many practical applications and is encountered in many fields in the form of heat exchange and heat removal from hot plates, positioned either horizontally or vertically. The former in particular, despite its practical relevance, has not been so deeply studied as the latter: there is in fact less literature available concerning natural convection on horizontal plane plates. Among the thematic researches there is that by Devia & Tanda [2], who experimentally investigated the heat exchange coefficient distribution in natural convection on rectangular plane plates of different dimensions. They found out that the values diminish significantly moving from external locations to internal ones. Kimura et al. [3] studied heat transfer in natural convection for water, at the environmental temperature, located onto a heated plate variably inclined. The instability of the flow on the plate causes, for elevate slopes, a detachment in correspondence to the most elevate location and so, when the fluid has crossed the whole surface towards the highest side, it detaches. For smaller slopes the detachment happens internally with respect to the surface and the same also for a null slope, where, in addition, the detachment happens exactly at the centre of the plate. In general one could say that heat removal and heat transfer coefficient are the main subject of the few researches available. Moreover still less researches have focused on experimental investigations of a possible relation between the thermal state of the system plate-fluid and the flow field induced in the fluid itself. It is in fact very hard to map the velocity field inside such a domain, because a huge number of sensors would be requested to give a statistical acceptability to the results obtained and this would also severely affect the reliability of the data measured as a consequence of relevant pressure losses. To overcome this difficulty it has to be hypothesised an alternative criterion, to study the flow field, based on a macroscopic indicator. Such a criterion was tested and verified by Lorenzini [4; 5; 6]. Its validity is limited to analyse only partially the flow patterns but, missing other criteria, it is for sure useful. This criterion is based on the observation that a thermal stratification in initially stationary air, located above a horizontal metallic hot plate, is associated to a macroscopic dynamic phenomenon due to buoyancy, consisting of a vertical force directed upwards originated by a partial conversion of thermal energy of the plate in mechanical energy of the air. This force can be analysed with a tracer, which was found to be a light coil made of polyethylene, free to rotate around a rod fixed to the hot plate. The flow field and particularly its general intensity is so qualified determining the angular velocity at which the coil rotates around the rod. The previously quoted publications demonstrated the existence of a relation between that angular velocity of the coil and the plate temperature T_p, but many other geometrical and thermal fluid dynamics parameters can affect the process and consequently alter the interpretation of the data. Among them the weight of the coil *P*, the effect of which on the angular velocity ω of the coil is going to be the main interest of this paper.

2. EXPERIMENTAL SETUP AND INTRODUCTION TO THE TESTS PERFORMED

The phenomenon analysed is as follows: the plate starts heating up and the air above it is interested by a thermal gradient and consequently by a buoyant effect. When the plate reaches a certain temperature then the light coil begins to rotate around the rod as buoyancy causes a vertical force acting upwards in the air medium which, due to the shape of the coil, is transferred, i.e. converted, to mechanical energy of rotation. The experimental apparatus used for this research is an evolution of that presented in [4; 5; 6]. In the present investigation, in fact, a higher number of characteristic parameters have been considered and consequently a broad number of coils was tested. In particular, as the turn width *L* assumed the values 10 and 20 mm, the number of turns N was took equal to 2 and the weight of the coil *P* assumed the values 1.0, 2.0, 3.0, 4.0 and 5.0 g, 10 different coils were employed for these tests. The weight *P*, main object of the present investigation, was varied by means of layers of aluminium tape added or subtracted. Figure 2.1 shows the essential schematic of the setup: a horizontal parallelepiped stainless steel plane plate with square bases is uniformly heated from below by four electric resistances (2 kW); a slender vertical rod is inserted in the centre of the plate and its tip holds a light coil of polyethylene (the coupling is aided by a coating made of Teflon). Checking the figure, the side Q is equal to 350 mm, enough to consider uniform the central temperature field; W is equal to 30 mm. A thermal insulation of polyurethane 200 mm thick covers five of the six sides of the plate, as showed in figure 2.1, during the tests to prevent any temperature shocks to the operators or deformations to the materials. A distance h of 60mm between the plate and the lowest point in the coil was constant in all the cases to have the same force acting on the system. The upper part of the coil is circular with a diameter equal to 30 mm. Being the coil conic, at each turn the diameter varies of an addendum 2*L* and so *D* is not a constant. The angle α between one turn and another is kept constantly equal to (π/6) rad. The plate temperature is measured by two digital thermometers characterised, according to the producer, by margin of error equal to 0.5%: their sensors are located in correspondence to the centre and to one side of the plate, due to the symmetry of the temperature field. A digital camcorder was used to record the tests and to transfer the results obtained to a pc for the final elaboration.

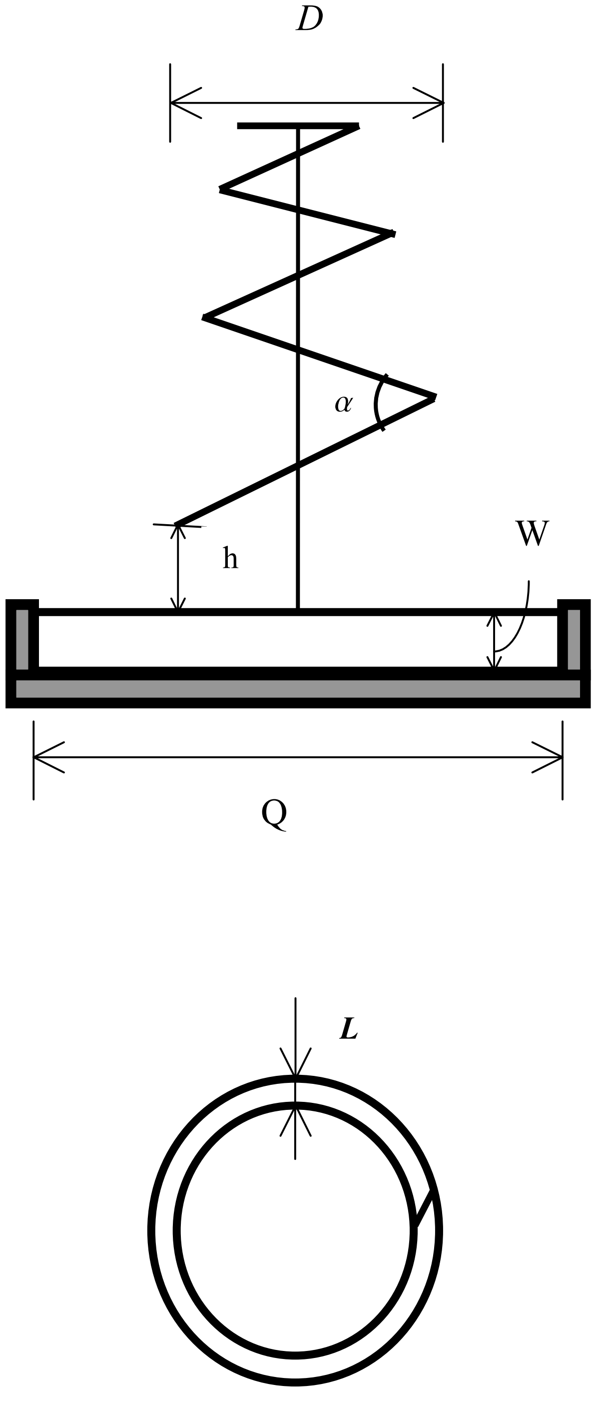


Figure 2.1 – Schematic of the experimental apparatus (top) and of a single turn (bottom).

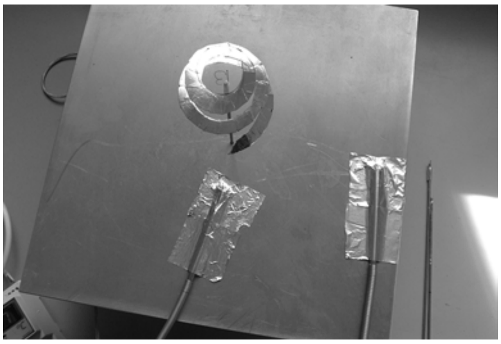


Photo 2.1 – Partial image of the apparatus in a non-operative stage.

In photo 2.1 it is shown a detail of the apparatus, in a non-operative stage, with one of the coils used for the tests here presented, characterised by N equal to 2. The experimental tests performed requested, as the very first stage of investigation, to have the steady condition reached, that is a full rotational equilibrium of the coil in a context of thermal fluid dynamics equilibrium of the whole system. This condition was taken as reached when the so called triggering temperature of the plate was obtained: i.e. that value allowing for a stable and constant rotation of the coil. The highest triggering temperature measured was of 64°C and so 65°C was the lowest value of T_p investigated, in order to be sure of always acting in steady state. When this condition was reached, the tests focused on recording the time requested by each coil for ending 30 complete revolutions around the vertical rod. To give statistical meaning to the results, each test was repeated 15 times, taking as “final result” a mean of the 13 intermediate values recorded. The analysis performed mainly focuses on the role that, in the process of energy conversion analysed in this study, plays the coil weight P as associated to a set of constant values of plate temperature T_p, turn width L and number of turns N. For all the tests performed, the air temperature, which is also a significant parameter even if here its relevance is not going to be taken into account, was always kept at 21°C thanks to a thermostat.

3. RESULTS

As the previous section has explained, the aim of the present paper is that of studying the effect that the weight of the coil P has on its angular velocity ω, that is on the process of energy conversion from thermal to mechanical here faced. Among the whole data set obtained during the tests performed, this section quotes those results representing the most statistically significant samples achieved. The trends determined are reported in the figures from 3.1 to 3.5, each of which split in two.

a)

b)

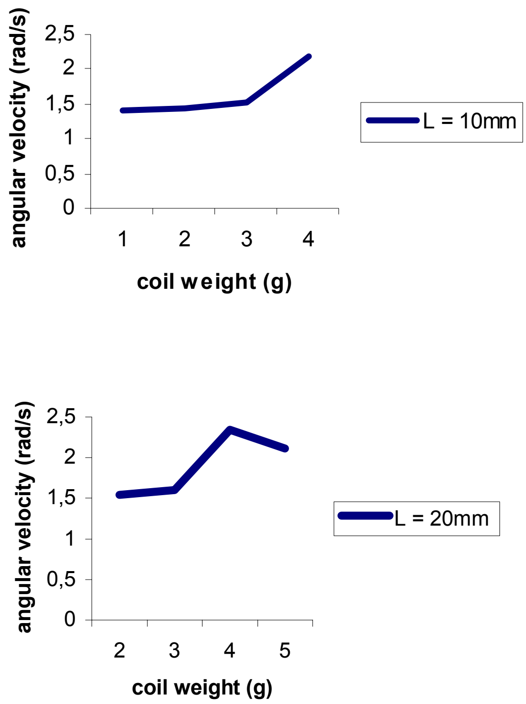


Figure 3.1 – Variables: angular velocity ω (rad s^{-1}) versus the coil weight P (g). Parameters: plate temperature T_p = 65.0°C, turn width L = 10 mm (a) or 20 mm (b).

a)

b)

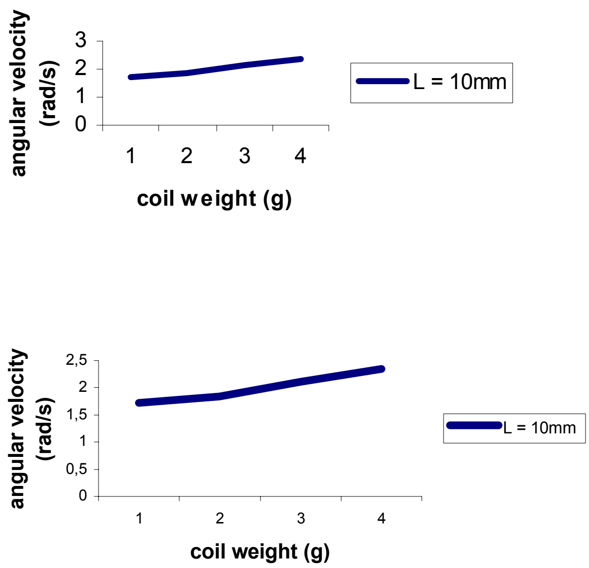
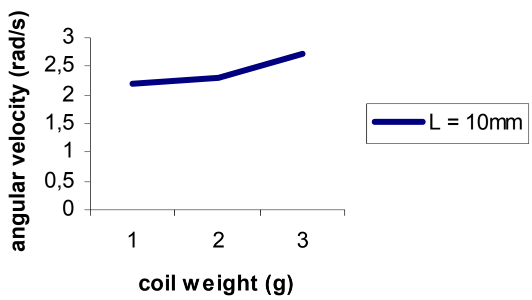


Figure 3.2 – Variables: angular velocity ω (rad s^{-1}) versus the coil weight P (g). Parameters: plate temperature T_p = 70.0°C, turn width L = 10 mm (a) or 20 mm (b).

In particular figure 1 reports the trends of the angular velocity ω with the coil weight P at a plate temperature T_p of 65.0°C and for a turn width L of 10 mm (a) or of 20 mm (b). Figure 2 instead reports the trends of the angular velocity ω with the coil weight P at a plate temperature T_p of 70.0°C and for a turn width L of 10 mm (a) or of 20 mm (b). Then, figure 3 reports the trends of the angular velocity ω with the coil weight P at a plate temperature T_p of 75.0°C and for a turn width L of 10 mm (a) or of 20 mm (b). Figure 4 reports the trends of the angular velocity ω with the coil weight P at a plate temperature T_p of 80.0°C and for a turn width L of 10 mm (a) or of 20 mm (b). Finally, figure 5 reports the trends of the angular velocity ω with the coil weight P at a plate temperature T_p of 85.0°C and for a turn width L of 10 mm (a) or of 20 mm (b).

a)



b)

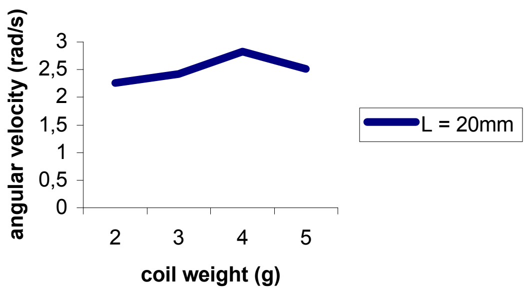
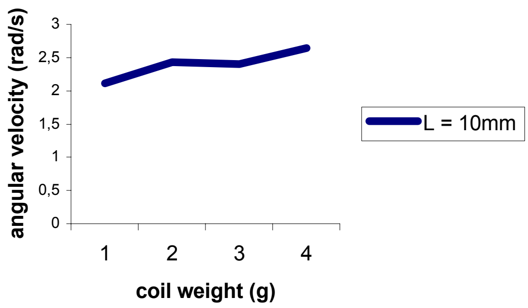


Figure 3.3 – Variables: angular velocity ω (rad s^{-1}) versus the coil weight P (g). Parameters: plate temperature T_p = 75.0°C, turn width L = 10 mm (a) or 20 mm (b).

The whole study was made for constant number of turns N, equal to 2. The study, so, allowed to analyse the dependence of ω on P at a fixed value of N, for two values of L and for each one of the values of T_p taken into consideration in the present investigation. As it is possible to observe, the trends seem to be quite articulated. One in fact would reasonably expect that the angular velocity ω always diminishes when the weight of it augments: actually this proved not to be always true, not just passing from test to test but even in each single trend. This means that, in particular conditions, heavier coils can rotate quicklier than lighter ones, despite all the boundary conditions associated to the process being exactly the same. The experimental data just presented seem apparently complicated by an unclear dependence of the dependent variable on the independent. However, even if facing a so difficult set of data, it just has to be found the correct interpretative key. The first consideration is that the presence of widely spread heterogeneous results, independently by the broad range of configurations studied and by the precise statistical criteria adopted in their elaboration, indicates the less characterising nature of the weight of the coil P as a factor affecting the angular velocity ω, of course in the range of configurations analysed, with respect, e.g., to the plate temperature T_p, whose relevance appears observing the figures here reported. It is important to stress out in the previous sentence that what stated, at this stage of the research, holds true "in the range of configurations analysed": one could expect, in fact, that heavy coils, that is coil characterised by values of P major than those here investigated, may follow the "normal" trend, meaning that heavier coils rotate slowlier.

a)



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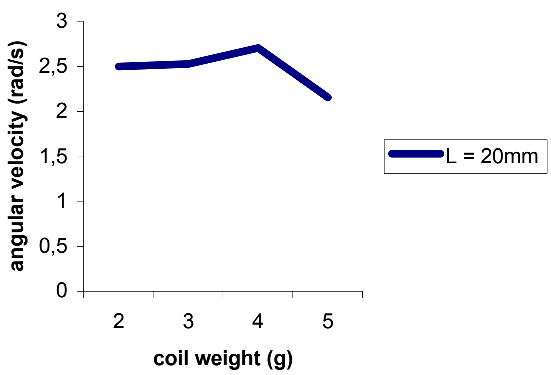
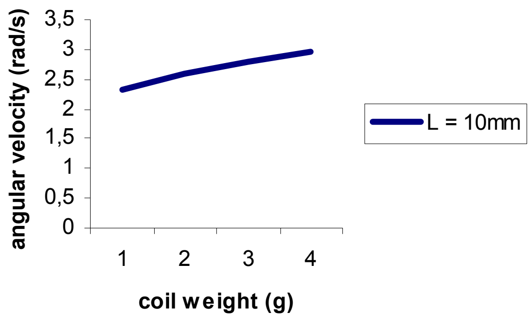


Figure 3.4 – Variables: angular velocity ω (rad s^{-1}) versus the coil weight P (g). Parameters: plate temperature T_p = 80.0°C, turn width L = 10 mm (a) or 20 mm (b).

This consideration is anyway supported also from what the figures here reported show: what, in fact, all the cases in analysis highlight is that when considering values of P between 1.0 and 4.0 g then the angular velocity ω of the coil increases with P; if, instead, one observes what happens passing from 4.0 to 5.0 g, then ω decreases in all the cases examined.
This, far from being a coincidence, could have a physical meaning: for very small values of the weight of the coil P, the dynamic resistance of air referred to the rotating coil can produce rotational instabilities which an increase in P reduces making the revolution more stable; for bigger values of P, greater than 4.0 g, the system may rotate more stably, as the coil is percentually less affected by the resistance of the medium with respect to the other components playing a role in the process and so an increase in P could cause the "normal" decrease of ω.

a)



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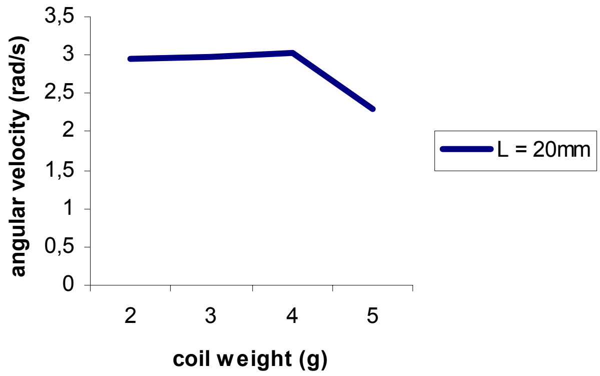

Figure 3.5 – Variables: angular velocity ω (rad s^{-1}) versus the coil weight P (g). Parameters: plate temperature T_p = 85.0°C, turn width L = 10 mm (a) or 20 mm (b).

4. CONCLUDING REMARKS

Energy is not only important at our times just in the sense of its production or management but also in that of its conversion from one form to another. Caring for the latter aspect, the present paper treats of a problem of conversion of thermal energy in mechanical. This process occurs when a horizontal plate is heated and reaches a higher temperature with respect to that of the surrounding environment: the thermal gradient generated in the air is able to modify the initial flow field. A vertical component of velocity directed upwards can so be transmitted to a light coil, suspended above the hot plate, which starts to rotate around a rod: this realises a partial conversion of thermal energy into mechanical. The present study was experimental and so an opportune setup was built and tested, first, and applied afterwards. The hot plate and the rod sustaining the coil were both made of stainless steel, while the coil was made of polyethylene to be light and stiff enough. In particular the investigation concerned the affection to the angular velocity ω of the coil by its weight P. The results proved that weight is not a strongly characterising parameter of the process, in the sense that a split sort of result was found in all cases. Actually the contradiction is just apparent, as a physical analysis of the results showed at the end of section 3 in the paper. The tests, in fact, showed that for values of P up to 4.0 g the angular velocity ω is directly proportional to P, while for bigger values the trend is inverted. As above indicated the contradiction is not real as the explanation to this duality relates to an analysis of rotational stability of the coil when subjected to buoyancy. Further research, involving also a new configuration of the setup, is at the moment in progress, as this process of conversion has to be deeply studied in all its component before a full knowledge of it and of its dynamics is reached.

NOMENCLATURE

D, outer diameter of the coil, mm
h, minimum distance between coil and plate, mm
L, turn width, mm
N, number of turns
P, coil weight, g
Q, aluminium plate side, mm
T_p, plate temperature, °C
W, aluminium plate width, mm
(greek symbols)
α, slope between two adjacent turns, rad
ω, angular velocity, rad s^{-1}

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