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Experimental analysis of the air flow field over a hot flat plate

Giulio Lorenzini *

Department of Agricultural Economics and Engineering, Alma Mater Studiorum-University of Bologna, viale Giuseppe Fanin, 50, 40127 Bologna, Italy

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Abstract

The present study relates to an experimental analysis of the flow field in the air above a flat, hot metallic plate in the absence of externally-induced streams. As widespread instrumentation of the domain was excluded in order to prevent measurements being affected by the sensors, in this work a criterion used in previous works by the same author was adopted, involving the use of a light coil as a partial tracer of the air flow field. The study measures the variation of the angular velocity of the coil with variations in the temperature of the hot plate beneath and other influencing parameters related to the geometry of the tracer. The results, in the case of a meanly regular behaviour in the broader sense described in the text, show a number of interesting particularities for lighter coils. The paper concludes with a numerical correlation of the experimental data, performed using the Mathematica® code, in order to extend the discrete results of the tests in a continuous way.

Keywords: Horizontal plate; Heat flux; Fluid dynamics; Coil; Angular velocity; Weight

1. Introduction

A hot flat plate put into contact with a colder, initially stationary fluid, generates in the latter a thermal stratification that creates a volumic mass gradient within [1]. This situation, presented above in a very general form, has a number of implications that subject studies have dealt with, covering a wide range of analysis in the field of heat exchange and heat removal in the vicinity of or inside the hot plate, positioned either horizontally or vertically. Despite the numerous applications, e.g. in the electronic field, heat transfer in natural convection from horizontal surfaces has been given less attention than that dedicated to vertical ones. With regard to the study of natural convection in the case of vertical plates, in [2] it is studied the thermal fluid dynamics behaviour of a system composed of air in a symmetrically heated vertical channel in which an auxiliary plate (adiabatic or interested by a constant thermal flux depending on the case studied) is positioned along its axial line, parallel to the channel walls. The work was aimed at optimising the channel geometry in order to improve its heat removal performance. The numerical analysis performed was held in steady state and for Rayleigh number values between 10^3 and 10^6. Results focused primarily on the effect that the auxiliary plate has on the thermal fluid dynamics behaviour inside the channel: the velocity trend, in particular, proved to be significantly modified by the presence of the plate due to the increased pressure losses. Buoyancy forces are also relevant in the work by Takhar et al. [3], who dealt with the process of heat exchange in a fluid thermally stratified to varying extents, depending on the direction considered, and which is vertically crossed at constant velocity by an isothermal vertical plate hotter than the fluid. The work, which was once again numerical, showed the influence that temperature stratification has on the dynamic and thermal field in the fluid, the latter being affected to a greater extent the higher the temperature gradient in the fluid. As mentioned previously, less literature is available on the question of natural convection on horizontal plane plates. The works available include a paper by Devia and Tanda [4], who analysed the heat exchange coefficient distribution in natural convection on rectangular plane plates of different dimensions by means of an optical technique. The results showed that such a distribution reflects the 3-D nature of the thermal field impending the surface and that the values diminish significantly from the outside towards the centre of the plate. Friedrich and Angirasa [5] numerically analysed the behaviour of a fluid subject to stable

* Tel.: +39 051 2096186.
E-mail address: giulio.lorenzini@unibo.it (G. Lorenzini).

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Nomenclature

D	outer diameter of the coil	mm
h	minimum distance between coil and plate	mm
H	total height of the coil	mm
L	turn width	mm
N	number of turns	
P	coil weight	g
Q	aluminium plate side	mm
R^2	quadratic coefficient of correlation	
T_a	air temperature	°C
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}

thermal stratification in conditions of convective heat exchange in a 2-D model. Precisely, the phenomena of stratification and convection take place below a horizontal heated plate facing downwards and therefore, because of the pressure difference between the hot plate and the colder flow coming from the sides, a horizontal pressure gradient is generated that leads the fluid flow towards the sides of the plate. Once the flow is no longer in contact with the surface, it will rise due to buoyancy: with regard to the research presented herein, it is very interesting to note how the initial motive force moves the fluid horizontally, due to the pressure gradient. Kimura et al. [6] on the other hand, studied the heat transfer in natural convection for a fluid (water at room temperature) on a heated plate inclined between 0 and $(\pi/9)$ rad at intervals of $(\pi/36)$ rad between positions. As the fluid is less dense towards the top and denser towards the bottom, the instability of the flow on the plate means that for large slopes, the fluid travels across the surface until it reaches the higher side, where it detaches. However, flow behaviour is less clear for smaller slopes: in this case one may have two flows coming from the two opposite sides of the plate that meet in a central location from where they detach. This applies for null slopes, even if with a full symmetry to system geometry. As this review of the literature on problems of natural convection in a fluid in contact with a flat plate demonstrates, few researches, especially in the experimental field, have investigated in depth the correlation between the thermal state of the plate-fluid system and the flow field induced inside the fluid, and in most cases they confined their work to an examination of the system with regard to heat removal and the calculation of the heat transfer coefficient (or Nusselt number in dimensionless terms). This choice is fully justified by the complexity of the question and by the impossibility of mapping the velocity field inside the domain analysed, because of the excessive use of sensors that would be required and that would cause an affection to the measured data due to the excessive pressure losses that would be produced. This drawback is difficult to overcome using experimental means, unless one hypothesises an alternative criterion to studying the flow field that is not linked to a punctual or statistical mapping of it, but rather based on the singling out of a macroscopic indicator. Such a criterion was hypothesised and subsequently verified in three recent publications by Lorenzini [7–9]. Although, due to its nature, the results obtained only partially describe the flow field and evidently do not provide a complete investigation of the whole topic, in the absence of other information, the indications given can be useful. The first observation made in the above-mentioned publications is that a thermal stratification in initially stationary air above a horizontal hot metallic plate, subject to the natural buoyancy induced by the volumic mass gradient alone, is associated to a macroscopic dynamic phenomenon. This consists of a real force created by the conversion of thermal energy from the plate into the mechanical energy of the fluid and can be analysed by means of a suitable tracer, namely a lightweight polyethylene coil, able to rotate around a rod fixed to the hot plate. This allows one to investigate many aspects of the dependence of the flow field, described by the angular velocity in rad s^{-1} at which the coil is moved due to plate temperature. A nearly-linear variation of coil velocity with plate temperature is observed. However, it goes without say that the study cannot be limited to these two parameters and a single coil configuration alone, but rather it must be extended to the other influential parameters, namely, in addition to plate temperature T_p in °C, air temperature T_a in °C, weight of the tracer used P in g, width L in mm of the single turn, number of turns N and diameter D in mm of the coil. This paper therefore aims to provide a detailed study of the flow field over a hot metallic plate, starting from the outlines provided by Lorenzini [7–9] and going on to expand the field of analysis to a wider range of influential parameters.

2. Experimental apparatus

The tests performed in [7–9] provided clear indications on the non-scalability of the phenomenon. This would seem rational as, with an equal temperature gradient in the air, variations to the scale of the apparatus do not affect the motive effect of the phenomenon but rather the weight of the coil alone: if the weight becomes too great the thrust due to buoyancy is insufficient to win the inertia caused by the contact between the coil and the tip of the rod. This matter was taken into account when designing the experimental apparatus, in order to minimise the effect of the weight of the coil so that it could be neglected when computing the dynamics of the process. Essentially the apparatus is composed of a uniformly heated horizontal plate, at the centre of which a slender vertical rod is fixed which holds the lightweight coil at its point of weight balance in order to allow balanced rotation (Fig. 1).

A material with high thermal conductivity and diffusivity was chosen for the hot plate, in order to obtain a uniform temperature and quick transient states in the domain consequent to

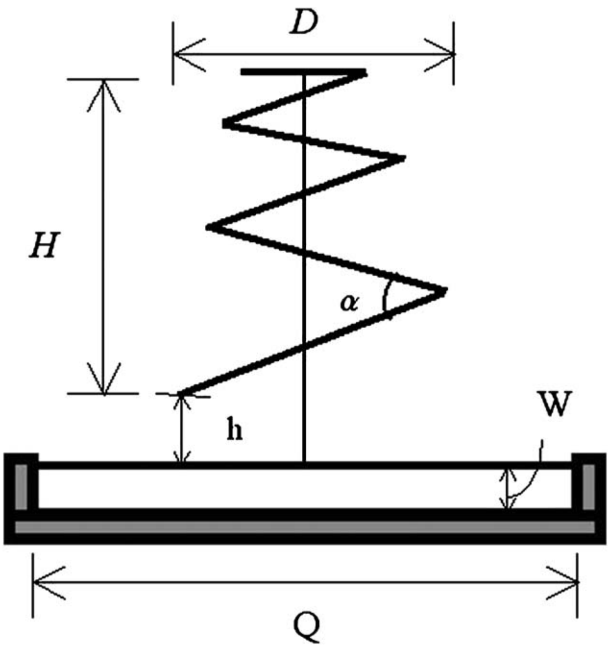

Fig. 1. Schematic: the kernel of the experimental apparatus.

plate temperature variations: in this case, stainless steel was selected because of its workability. The plate was shaped to take on a parallelepiped form with square bases in order to obtain uniform thermal behaviour in both plane directions. The plate dimensions are wide enough to neglect the checkerboard effects in the centre: both the bases have a side Q of 350 mm; the thickness W is equal to 30 mm. In operating conditions, in order to ensure safety against of the high temperatures reached and to reduce heat dispersions and thermal unevenness, the plate, with the exception of its upper surface, was insulated using 20 mm thick layers of expanded polyurethane. A non-through hole with a depth of 15 mm and a diameter of 2 mm allows the rod holding the coil to be fixed in a vertical position in the centre of the plate. The stainless steel rods also have a cross sectional diameter of 2 mm in order to obtain a good fit with the corresponding hole. Depending on the tests performed and on the coil used, rods with different lengths were used in order to keep the distance h in mm between the plate and the lowest point in the coil 60 mm at all times: this guarantees the same dynamic action on the free end of the coil. The coupling between rod and coil was made using a suitably shaped tip (for the former) and upper portion of the latter (covered with a Teflon layer), in order to minimise friction. The conic profile coil hung over the rod is made of polyethylene, a lightweight but fairly stiff material. Lightness proved to be fundamental to minimising the friction in the rod-coil contact; stiffness is useful in minimising the oscillatory strains of the coil. The upper part of the coil (in contact with the tip of the rod) was circular with a diameter equal to 30 mm, for all the cases analysed. The number of turns N and the width L in mm (see Fig. 2) varied from one test to another, as will be explained below. The diameter of the coils therefore increases towards the bottom by an addendum $2L$ at each new turn. This means that the maximum diameter D in mm of the coil assumes different values depending on the case analysed. As the width of each turn L in mm is one of the parameters examined in the present study, three different values were tested: 10, 15 and 20 mm.

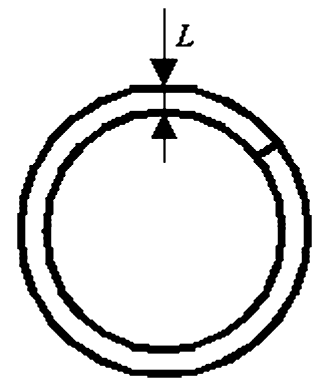

Fig. 2. Schematic: width of a turn L in mm.

Another geometric parameter considered in the present experimental analysis is the number of turns N of which any one coil is composed: the values chosen were 2, 3 and 4, whilst the slope α between one turn and another was always kept equal to $(\pi/6)$ rad. The weight of the coils, a fundamental parameter of this study, is obviously linked to the material used and to the number and width of the turns: therefore, in order to lead all the weights to a range of common values it is necessary to be able to vary it. Aluminium tape was therefore added or removed as required, in order to obtain the weight P in g desired, which ranged between 1.0 and 6.0 g. Another property that led to the choice of aluminium tape is that being so thin, variations to the turns was negligible and therefore it did not cause significant detriment to the aerodynamics of the coil when in motion, due also to the reduced velocities of rotation. Another fundamental parameter, plate temperature, assumed different values thanks to the use of four electric resistances, each one with a rated power of 500 W, in contact with the under-surface of the plate and powered by a Variac transformer. The instrumentation system used to measure plate temperature is composed of two digital thermometers with 0.5% error margins according to the producer, which is acceptable for the kind of investigation carried out and to the thermal gaps analysed. The sensor of each thermometer was a probe in direct contact with the plate. The probe has a thermal resistance sensor which is effective in a temperature range of 0–350 °C. Externally, it is coated in stainless steel AISI316 and fixed to the plate using aluminium glue and tape in order to guarantee the slightest possible thermal contact resistance. It was not necessary to adopt thermocouples as the tests always concerned measurements in steady state and so the readiness of the instrument was not as essential as instead its precision, which was adequate using the digital thermometers chosen. For a suitable mapping of the temperature field of the plate one probe was positioned near to the centre of the plate and another was positioned more externally, as shown in Fig. 3 (detail of the apparatus in a non-operative stage, for the case of a coil with 2 turns).

Each test was performed in conditions of stability and uniformity of plate temperature only. The plate temperatures investigated were chosen using the criterion that will be described in

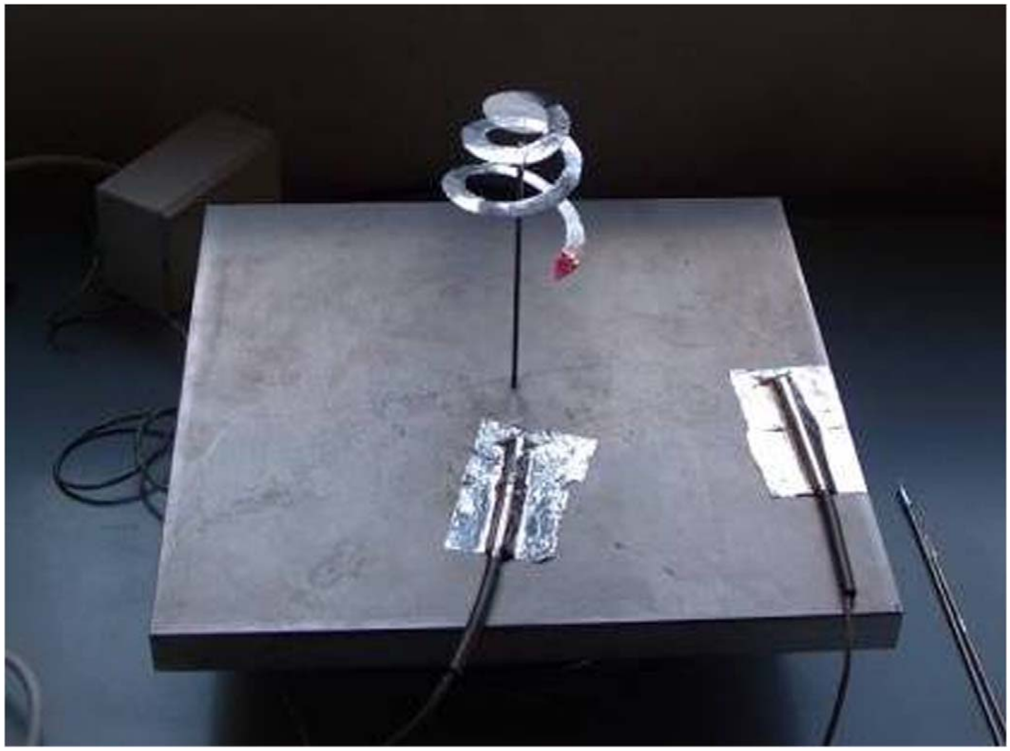

Fig. 3. Experimental apparatus: coil with 2 turns, thermometric probes and plate without lateral thermal insulation (photo taken in a non-operative stage).

detail in the section concerning the tests performed. The velocity of coil rotation was then recorded using a digital camcorder connected to a PC.

3. Experimental tests and results

The main purpose of the present experimental study is to look for a correlation between thermal stratification of the air, due to a horizontal hot plate, and the dynamics induced by it in the flow field of a suspended lightweight coil, in steady state expected and verified case by case. In particular, starting from the many variables of the matter, the dependence of the angular velocity impressed at the coil by the weight of the coil and plate temperature was studied: it is, in fact, believed that they have an extremely relevant effect on the dynamics of the phenomenon, even in a synergic way. The other variables that influence the process were treated as constant parameters in each test by varying their values from one test to another, whereas room temperature T_a was kept constant at 21 °C by means of a thermostat. In particular, of the parameters: the number of turns N assumed values of 2, 3 and 4; the width of turn L in mm values of 10, 15 and 20 mm. The two quantities held as variables of the study assumed the following values: the weight of the coil P in g ranged between 1.0 and 6.0 g with steps of 1.0 g; the plate temperature T_p in °C was equal to 65.0, 70.0, 75.0, 80.0, 85.0 °C. Between one plate temperature value and another steps of 5.0 °C were adopted in order to obtain sufficient differentiation to avoid overlaps due to experimental error. The choice of the values of T_p in °C investigated were consequent to the preliminary tests, performed in order to determine the triggering temperatures of the dynamic phenomenon in the different coil configurations considered. “Triggering temperature” is taken to mean the temperature at which the rotation of the coil becomes stable and the associated phenomenon reaches the steady state in well defined conditions. The upper limit of the triggering temperatures was set at $T_p = 64.0$ °C in all the cases analysed. For this reason the tests were performed for plate temperatures $\geqslant 65.0$ °C, in order to be certain of the presence of the phenomenon in stable form, regardless of the configuration of the system investigated. The criterion used to acquire the angular velocity of the coil ω in rad s^{-1} was obviously of a statistical nature, performing 15 repetitions for each single test and assuming as a final value the mean of the 13 intermediate values, having discarded the highest and the lowest values. Each test consisted in measuring the time required by the coil to complete 30 full revolutions, observed precisely using a digital camcorder connected to a PC. The most interesting statistical results of those experimentally obtained with the different coil configurations considered are given in Tables 1–6. With regard to the effect that the independent variable T_p in °C has on the angular velocity of the coil ω in rad s^{-1}, it is evident that in all the cases analysed an increase in the former strongly affects the latter, in agreement with the first partial tests reported by Lorenzini [9]. The effect proves to be greater for lower values of P in g and this appears rational as any “motive cause” is reduced by the frictional effect, proportional to the weight, acting on the system interested by the dynamic action studied. As the experimental data acquired and considered valid proved sufficient grounds for a more detailed analysis of the topic, as described below, work also focused on observing the functions of correlation between ω in rad s^{-1} and T_p in °C with changes in the parameter P in g. With regard to the trend of angular velocity

Table 1
Variation in angular velocity in rad s^{-1} with plate temperature T_p in °C and with coil weight P in g (number of turns $N = 2$; turn width $L = 10$ mm)

ω [rad s^{-1}]		P [g]		
		1.0	2.0	3.0
T_p [°C]	65.0	2.61	2.48	2.75
	70.0	3.38	3.11	2.98
	75.0	3.90	3.18	3.25
	80.0	3.96	4.31	3.44
	85.0	4.11	4.69	3.61

Table 2
Variation in angular velocity in rad s^{-1} with plate temperature T_p in °C and with coil weight P in g (number of turns $N = 2$; turn width $L = 15$ mm)

ω [rad s^{-1}]		P [g]		
		1.0	2.0	3.0
T_p [°C]	65.0	3.12	1.88	2.63
	70.0	3.49	2.10	2.75
	75.0	3.52	2.61	3.16
	80.0	3.99	3.16	3.30
	85.0	5.33	4.19	3.99

ω in rad s^{-1} with the weight of the coil P in g, results proved to be more articulated, not only in the overall trend but also in single partial trends. It could in fact be hypothesised that the angular velocity of the coil always diminishes with an increase in weight: in actual fact, this was not always found to be true, so a clear analysis of the causes will have to follow the results set out below. For instance, if one considers the first case shown in Table 1 ($L = 10$ mm; $N = 2$), the trend appears rather irregular.

In fact, ω in rad s^{-1} diminishes with weight in a strictly monotonic way in correspondence to a value of T_p equal to 70.0 °C only, whereas for the two highest values of plate temperature the maximum ω in rad s^{-1} is observed for $P = 2$ g and the minimum for $P = 3$ g; for $T_p = 65.0$ °C and $T_p = 75.0$ °C an opposite trend is recorded, with the minimum of ω in rad s^{-1} in the case of the coil with intermediate weight. A similar trend was also encountered in the case $L = 15$ mm, $N = 2$ (see Table 2), where for $T_p = 85.0$ °C only the angular velocity ω in rad s^{-1} decreases with the weight P in g, whereas in the other cases the relative minimum of ω in rad s^{-1} is always found for $P = 2.0$ g.

Similarly, in three out of the five cases studied in Table 3 ($N = 4$; $L = 10$ mm), angular velocity is lowest for a coil weight of 3.0 g, halfway between 2.0 and 4.0 g, the extremes of the interval considered.

If, on the other hand, the turn width is equal to 10 mm and the number of turns is 3 (Table 4), the trend of ω in rad s^{-1} with the four values of the coil weight considered for this test, becomes apparently irregular for each value of T_p in °C analysed, in exactly the same way as the case $L = 20$ mm $N = 2$ presented in Table 5.

This is particularly true for the two lowest values of P in g whereas, as shown in Table 4 and in Table 5, for the two highest weight values, ω in rad s^{-1} increases with coil weight. An examination of this experimental data on the trend of angular velocity ω in rad s^{-1} with variations of the weight of the coil

Table 3
Variation in angular velocity in rad s^{-1} with plate temperature T_p in °C and with the coil weight P in g (number of turns $N = 4$; turn width $L = 10$ mm)

ω [rad s^{-1}]		P [g]		
		2.0	3.0	4.0
T_p [°C]	65.0	3.54	3.87	3.73
	70.0	5.87	5.01	5.00
	75.0	6.15	5.28	5.66
	80.0	6.66	5.36	5.82
	85.0	6.80	5.83	5.91

Table 4
Variation in angular velocity in rad s^{-1} with plate temperature T_p in °C and with coil weight P in g (number of turns $N = 3$; turn width $L = 10$ mm)

ω [rad s^{-1}]		P [g]			
		1.0	2.0	3.0	4.0
T_p [°C]	65.0	1.49	2.78	1.20	1.31
	70.0	2.34	2.90	1.70	1.89
	75.0	2.74	2.98	1.91	2.37
	80.0	3.07	3.08	2.49	2.70
	85.0	3.72	3.40	2.73	3.19

Table 5
Variation in angular velocity in rad s^{-1} with plate temperature T_p in °C and with coil weight P in g (number of turns $N = 2$; turn width $L = 20$ mm)

ω [rad s^{-1}]		P [g]			
		2.0	3.0	4.0	5.0
T_p[°C]	65.0	1.69	1.88	0.89	0.94
	70.0	2.19	2.30	1.33	1.54
	75.0	2.36	2.53	1.41	1.60
	80.0	2.50	2.58	1.44	2.26
	85.0	3.06	2.77	1.59	2.28

Table 6
Variation in angular velocity in rad s^{-1} with plate temperature T_p in °C and with coil weight P in g (number of turns $N = 4$; turn width $L = 15$ mm)

ω [rad s^{-1}]		P [g]		
		4.0	5.0	6.0
T_p(°C)	65.0	3.89	4.24	2.43
	70.0	5.03	4.52	3.11
	75.0	5.27	4.63	3.74
	80.0	5.51	4.69	3.92
	85.0	5.53	4.86	3.96

P in g, would appear to be complicated by a not evident dependence between variables. When such heterogeneous data is obtained, finding the correct interpretative key is fundamental. The first consideration to be made is that the presence of results that are in part contrasting, regardless of the wide range of configurations considered and the precise statistical criteria adopted in processing the data, indicates that the weight of the coil P in g, in the range of configurations analysed, proves to be a less characterising factor, with regard to phenomenological dynamics, than plate temperature T_p in °C. In this statement it is important to underline “in the range of configurations analysed” as the matters raised below are obviously only valid for low weight values. Heavy coils could be strongly affected by friction at the rod-coil contact point, which would probably invalidate this statement.

However, the data set is made clearer by examining Tables 1–6, which show that a random appearance of the data only remains if one considers values of P in g lower than 4.0 g, whereas between 4.0 and 6.0 g all data agree in singling out a decrease in the angular velocity of the coil with an increase in weight, as one would expect aprioristically. The matter becomes clearer with the cases presented in Table 6 ($L = 15$ mm; $N = 4$), where ω in rad s^{-1} decreases strictly monotonically at each test, with the exception of the lowest plate temperature case, thus presenting an anomaly. Further investigations are obviously required, involving wider ranges of values of P in g.

Nevertheless, at present it is believed that the reason for such a dualism in the data obtained can be attributed to the fact that, for very small coil weight values, the dynamic resistance of the medium (i.e. air) in relation to the rotating coil can produce anomalies causing an obstacle percentually relevant when compared to all the dynamic components present during rotation. Such a possibility, which is well known in the worlds of aerodynamics and chemical dispersions, has been encountered many times, also in very different scientific fields, such as sprinkler irrigation where particularly small droplets could invert the usual time of flight law typical of larger droplets, because of the dynamic resistance of the medium [10]. This could explain the uncertainty noted in the flow field for very small values of P in g: in that it could become indefinable without also analysing the contribution by other factors such as air friction. For higher coil weight values (greater than 4.0 g) the system proves to be more stable in its rotation, because it is percentually less affected by flow field disturbances due to the resistance of the medium. This, therefore allows the velocity field to assume its normal configuration, which implies that heavier coils rotate slower than lighter coils.

4. Numerical correlation of the experimental data collected

In the previous section the examination and discussion of the main experimental results obtained in this research showed how the process studied highlights, from a phenomenological point of view, the existence of a clear link between the parameters considered: the dependent variable ω in rad s^{-1}, on the one hand, and the independent variables/parameters plate temperature T_p in °C, coil weight P in g, number of turns N and turn width L in mm, on the other. For this reason, it was investigated which numerical correlations could describe those trends. This type of in depth research could also prove interesting with a view to extending the trend of the phenomenon reported in the results section to a wider range of non-discrete values and therefore to generalising the study towards wider applicability. Given that a single mathematical relation can explicitly solve a problem of dependence between just two variables, as there are 4 variables that potentially affect ω in rad s^{-1}, once again we adopted the criterion of considering plate temperature T_p in °C as an independent variable, using P in g, N and L in mm as parameters to which a different value was assigned in each case.

Table 7
Interpolating function $\omega(T_p)$ for the two different correlation models adopted (LIN = Linear; EXP = Exponential) with variations in coil weight P in g (number of turns $N = 2$; coil width $L = 10$ mm)

P [g]	$\omega(T_p)$ (Interpolating function)	R^2
1.0 LIN	$\omega = 0.358T_p + 2.518$	0.85
1.0 EXP	$\omega = 2.574e^{0.107\ Tp}$	0.82
2.0 LIN	$\omega = 0.562T_p + 1.868$	0.94
2.0 EXP	$\omega = 2.141e^{0.160\ Tp}$	0.95
3.0 LIN	$\omega = 0.218T_p + 2.552$	0.99
3.0 EXP	$\omega = 2.596e^{0.069\ Tp}$	0.99

Table 8
Interpolating function $\omega(T_p)$ for the two different correlation models adopted (LIN = Linear; EXP = Exponential) with variations in coil weight P in g (number of turns $N = 2$; coil width $L = 15$ mm)

z	$\omega(T_p)$ (Interpolating function)	R^2
1.0 LIN	$\omega = 0.492T_p + 2.414$	0.81
1.0 EXP	$\omega = 2.662e^{0.121\ Tp}$	0.86
2.0 LIN	$\omega = 0.568T_p + 1.084$	0.94
2.0 EXP	$\omega = 1.462e^{0.201\ Tp}$	0.98
3.0 LIN	$\omega = 0.327T_p + 2.185$	0.92
3.0 EXP	$\omega = 2.309e^{0.102\ Tp}$	0.95

The correlation of the experimental data was performed using numerical code Mathematica® version 4.2, a widely used scientific software program. Fitting a set of variables in a limited range of values requires a careful choice of the interpolating function to be used, although one must bear in mind that the description may have a merely local validity as the relation between variables could be different in different intervals. The local criterion used to single out the best mathematical law in approximating the experimental data set available is based on the best fit technique, that is by verifying which function locally maximises the quadratic coefficient of correlation R^2. The results obtained led to the choice of the linear and exponential models, although the former generally appears to be preferable, as the study in [9] also suggests. In actual fact, even for comparable R^2, it is more elementary and therefore easy to apply in practical applications. In particular Tables 7–12 show, for the case studies summarised in the Tables 1–6 respectively, the interpolating relations determined and the relative values of R^2, using both linear and exponential models.

Table 7, where $N = 2$ and $L = 10$ mm are held constant, shows the set of interpolating functions $\omega(T_p)$ for P in g with values of 1.0, 2.0 and 3.0 g.

Table 8, where $N = 2$ and $L = 15$ mm are held constant, shows the set of interpolating functions $\omega(T_p)$ for P in g with values of 1.0, 2.0 and 3.0 g.

Table 9, where $N = 4$ and $L = 10$ mm are held constant, shows the set of interpolating functions $\omega(T_p)$ for P in g with values of 2.0, 3.0 and 4.0 g.

Table 10, where $N = 3$ and $L = 10$ mm are held constant, shows the set of interpolating functions $\omega(T_p)$ for P in g with values of 1.0, 2.0, 3.0 and 4.0 g.

Table 9
Interpolating function $\omega(T_p)$ for the two different correlation models adopted (LIN = Linear; EXP = Exponential) with variations in coil weight P in g (number of turns $N = 4$; coil width $L = 10$ mm)

P [g]	$\omega(T_p)$ (Interpolating function)	R^2
2.0 LIN	$\omega = 0.731T_p + 3.611$	0.77
2.0 EXP	$\omega = 3.681e^{0.143\,Tp}$	0.71
3.0 LIN	$\omega = 0.427T_p + 3.789$	0.85
3.0 EXP	$\omega = 3.850e^{0.089\,Tp}$	0.81
4.0 LIN	$\omega = 0.518T_p + 3.670$	0.81
4.0 EXP	$\omega = 3.735e^{0.107\,Tp}$	0.78

Table 10
Interpolating function $\omega(T_p)$ for the two different correlation models adopted (LIN = Linear; EXP = Exponential) with variations in coil weight P in g (number of turns $N = 3$; coil width $L = 10$ mm)

P [g]	$\omega(T_p)$ (Interpolating function)	R^2
1.0 LIN	$\omega = 0.519T_p + 1.115$	0.97
1.0 EXP	$\omega = 1.361e^{0.210\,Tp}$	0.93
2.0 LIN	$\omega = 0.142T_p + 2.602$	0.91
2.0 EXP	$\omega = 2.629e^{0.046\,Tp}$	0.93
3.0 LIN	$\omega = 0.383T_p + 0.859$	0.98
3.0 EXP	$\omega = 1.056e^{0.201\,Tp}$	0.96
4.0 LIN	$\omega = 0.479T_p + 0.833$	0.98
4.0 EXP	$\omega = 1.076e^{0.231\,Tp}$	0.93

Table 11
Interpolating function $\omega(T_p)$ for the two different correlation models adopted (LIN = Linear; EXP = Exponential) with variations in coil weight P in g (number of turns $N = 2$; coil width $L = 20$ mm)

P [g]	$\omega(T_p)$ (Interpolating function)	R^2
2.0 LIN	$\omega = 0.305T_p + 1.445$	0.94
2.0 EXP	$\omega = 1.560e^{0.132\,Tp}$	0.94
3.0 LIN	$\omega = 0.206T_p + 1.794$	0.91
3.0 EXP	$\omega = 1.831e^{0.089\,Tp}$	0.88
4.0 LIN	$\omega = 0.151T_p + 0.879$	0.82
4.0 EXP	$\omega = 0.901e^{0.124\,Tp}$	0.76
5.0 LIN	$\omega = 0.340T_p + 0.704$	0.92
5.0 EXP	$\omega = 0.860e^{0.216\,Tp}$	0.88

Table 12
Interpolating function $\omega(T_p)$ for the two different correlation models adopted (LIN = Linear; EXP = Exponential) with variations in coil weight P in g (number of turns $N = 4$; coil width $L = 15$ mm)

P [g]	$\omega(T_p)$ (Interpolating function)	R^2
4.0 LIN	$\omega = 0.376T_p + 3.918$	0.77
4.0 EXP	$\omega = 3.944e^{0.080\,Tp}$	0.74
5.0 LIN	$\omega = 0.141T_p + 4.165$	0.94
5.0 EXP	$\omega = 4.176e^{0.031\,Tp}$	0.93
6.0 LIN	$\omega = 0.387T_p + 2.271$	0.87
6.0 EXP	$\omega = 2.350e^{0.121\,Tp}$	0.84

Table 11, where $N = 2$ and $L = 20$ mm are held constant, shows the set of interpolating functions $\omega(T_p)$ for P in g with values of 2.0, 3.0, 4.0 and 5.0 g.

Table 12, where $N = 4$ and $L = 15$ mm are held constant, shows the set of interpolating functions $\omega(T_p)$ for P in g with values of 4.0, 5.0 and 6.0 g. One can therefore state, with satisfactory approximation, on the basis of the values of R^2 found, that the angular velocity function of a coil shaped body subject to thermal stratification as presented in this paper, linearly increases with plate temperature, which is responsible for the temperature gradient in question.

It is useful to remember that this statement finds full justification in the thermal range analysed only, as the generalised application of the correlations given in Tables 7–12 could give rise to substantial errors in different temperature intervals, a matter that will have to be investigated in future studies in order to obtain a full mapping of the $\omega(T_p)$ function, at least for the most typical temperatures of thermal fluid dynamics applications.

5. Conclusions

This research studies by experimental means the flow field in the environmental air above a hot horizontal metallic plate. As a statistically relevant instrumentation of the system in question was excluded, a special criterion was chosen on which to base observations and measurements, with the choice of the angular velocity, induced by the dynamic action of thermal stratification, of a lightweight coil suspended over the hot plate and acting as a dynamic tracer. The study, presented as parametric analysis, related to the stable steady state consequent to the singling out, in the many cases examined, of the conditions that trigger the phenomenon. The system variables considered were: plate temperature (T_p in °C), coil weight (P in g), turn width (L in mm) and number of turns (N); an additional variable, which is potentially influential but not investigated in this paper, is environmental air temperature (T_a in °C), which was always kept equal to 21 °C in the tests performed. Once a suitable experimental set up had been constructed, a battery of tests was performed, each one repeated 15 times in order to comply with the correct criteria of statistical analysis of the data collected, by varying the parameters mentioned above. The tests showed that coil weight certainly has a considerable influence on the angular velocity of the system, however, the most interesting point was that an increase of the weight did not lead to a decrease in velocity in all cases and furthermore, if the other parameters remain constant, it would appear that coils with a smaller turn width are more affected by weight variations. In particular, the situation only becomes regular for values of P in g greater than 4.0 g. It is believed that this peculiarity arises due to the fact that for very small coil weights, air friction cannot be neglected, whereas for higher coil weight values, air friction is relatively less important: this consideration leaves ample scope for further investigations. As observed in most cases, the number of turns N also seems to have a significant influence: when it increases, if the other parameters remain constant, in most cases an increment in the angular velocity of the coil can be observed. Less influential on the phenomenon, at least with regard to this investigation, is the turn width L in mm. On the contrary, the effect that plate temperature T_p in °C has on the variation of the angular velocity is undeniably important: higher temperatures cause bigger angular velocities as the dynamic effect of the thermal gradient induced in the air above the plate is more intense. In order to provide a more in depth analysis of the influence that plate temperature has on the flow field of the system and how to extend the results obtained to a wider temperature range than that experimentally analysed, the study concluded by calculating the functions of correlation $\omega(T_p)$ that link angular velocity to plate temperature, on the basis of the experimental data collected. The best-fit numerical technique showed how the dependence of the dependent variable on the independent one can be expressed both in terms of an exponential and a linear relation, as the coefficient of correlation R^2 is almost equivalent. At the present time, this makes the latter preferable in the name of simplicity and for comparison purposes. However, this result can only be applied with precision in the vicinity of the temperature interval for which it was determined, bearing in mind that for different values and thermal intervals it could be very far from the results obtained in this study, being described by other functions that further studies will have to verify.

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