ANALYTICAL APPROACH FOR ESTIMATING THE PRESSURE DROP POTENTIAL IN CONVECTIVE VORTEX HEAT ENGINES

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ABSTRACT

This paper presents a new analytical approach for estimating the pressure drop potential in proposed technical concepts in which convective vortices are to be used as heat engines. The main novelty is analytical connection of the well-known CAPE value with the magnitude of the pressure potential. The proposed analytical approach is important and useful for research in energy concepts where convective vortices are to be used as sources of mechanical work for electricity production. Furthermore, it is the first approach developed by which the pressure drop potential can be calculated for concepts utilising convective vortex heat engines, and it is an important step forward for the theoretical research of alternative energy concepts with convective vortices.

Keywords: convective vortices; pressure drop potential; thermodynamic efficiency.

APPROCHE ANALYTIQUE POUR ESTIMER LE POTENTIEL DE BAISSE DE PRESSION DANS LES MOTEURS THERMIQUES CONVECTIFS VORTEX

RÉSUMÉ

Cet article présente une nouvelle approche analytique pour estimer le potentiel de baisse de pression dans les concepts techniques proposés dans laquelle des tourbillons convectifs sont utilisés comme moteurs thermiques. La principale nouveauté est un cadre d'analyse de la valeur bien connue CAPE avec la magnitude du potentiel de pression. L'approche analytique proposée est importante et utile pour la recherche dans les concepts de l'énergie où les tourbillons de convection doivent être utilisés comme sources de travail mécanique pour la production d'électricité. En outre, c'est la première approche développée par laquelle le potentiel de baisse de pression peut être calculé pour des concepts qui exploitent les moteurs thermiques de convection vortex, et il s'agit d'un important pas en avant pour la recherche théorique des concepts d'énergies alternatives avec tourbillons convectifs.

Mots-clés : tourbillons convectifs ; potentiel de baisse de pression ; efficacité thermodynamique.

1. INTRODUCTION

From an engineering perspective, research on convective vortices is interesting because of their potential use as sources of mechanical work. Specifically, convective vortices can be implemented as heat engines, and the generated mechanical work can be used to produce electricity. Convective vortices commonly found in nature include dust devils, tornadoes and waterspouts. These natural phenomena were the initial motivation for this research because of the strong physical evidence that convective vortices can be established in the surrounding atmosphere. The first proposal for the possible technical utilisation of convective vortices as heat engines in power plants was made by Michaud [1–2] and was based on his earlier work [3–5]. Michaud presented the AVE concept (Atmospheric vortex engine) [2] which is the first serious technical proposal for the establishment of the large scale prototype plant. According to the Fig. 1, the main part of the proposed AVE concept is gravitational vortex which in the physical sense acts as a chimney. Pressure difference is used to drive turbines and finally to produce electricity. Heat input is ensured in the form of waste industrial heat, so with the establishment of the AVE concept, overall efficiency of existing power plants could be increased. Michaud established the AVEtec Company and with his team still works on the development of the small scale prototype AVE models. Recently his company was funded with 300,000 USD from the Thiel foundation for the research of the AVE concept. Certainly, the development of the large scale AVE plant will be a technical challenge. An important question is how to repeatedly create and then control this powerful heat engine. The previously mentioned detail will be very hard to explain and CFD analysis could be an appropriate way to explore the behaviour of different working regimes. The AVE concept is at the moment the only technical concept with the most potential for a technical realisation. However, serious research is still needed for the preparation of the large scale AVE plant and to predict possible technical problems. An alternative idea for a solar power plant with a short diffuser was proposed by Ninic and Nizetic [6]. For this design the chimney, which had a limited height similar to that associated with the concept of a solar chimney power plant [7, 8], was replaced with a convective vortex. In all of the previous research, the convective vortex (gravitational vortex) is the central and most sensitive part of the research, due to its complexity [9]. Can we manage to produce repeatable convective vortices artificially and successfully control them as nature does? This question is obviously difficult to answer without serious and organised research on this topic, and the focus of this research should be directed towards convective vortices as flow objects. The potential benefits of the previously proposed concepts [1, 6] are significant; if we manage to succeed at implementing these concepts, we will be able to produce carbon-free electricity from renewable solar energy. Furthermore, we could increase the overall efficiency of existing thermal plants by using waste industrial heat as the input to the convective vortex system, instead of using cooling towers to eliminate the excess heat.

The pressure drop potential is a very important parameter in a system of convective vortices because it directly determines the magnitude of the convective vortices. There is a similarity to solar chimney power plants [10], in which the achieved pressure drop potential determines the quantity of mechanical work produced, which in turn determines the amount of electricity produced. There are a few theoretical and very important models of convective vortices developed by meteorologists that will be discussed in detail in the next section of the paper, but common to all those models is the fact that they do not realise convective vortices as a potential source of mechanical work for electricity production.

However, the theoretical models of convective vortices that have been developed by meteorologists are crucial because their research results provide the basis for the further development of physical and analytical models of convective vortex heat engines. For the concept proposed in [6], a theoretical model for a convective vortex is developed, and details can be found in [11, 12]. However, a general review of concepts in which convective vortices are utilised as heat engines can be found in [13].

The objective of this paper is to establish an alternative analytical approach for estimating the pressure drop potential in convective vortex heat engines. Proposed analytical approach includes CAPE value (con-

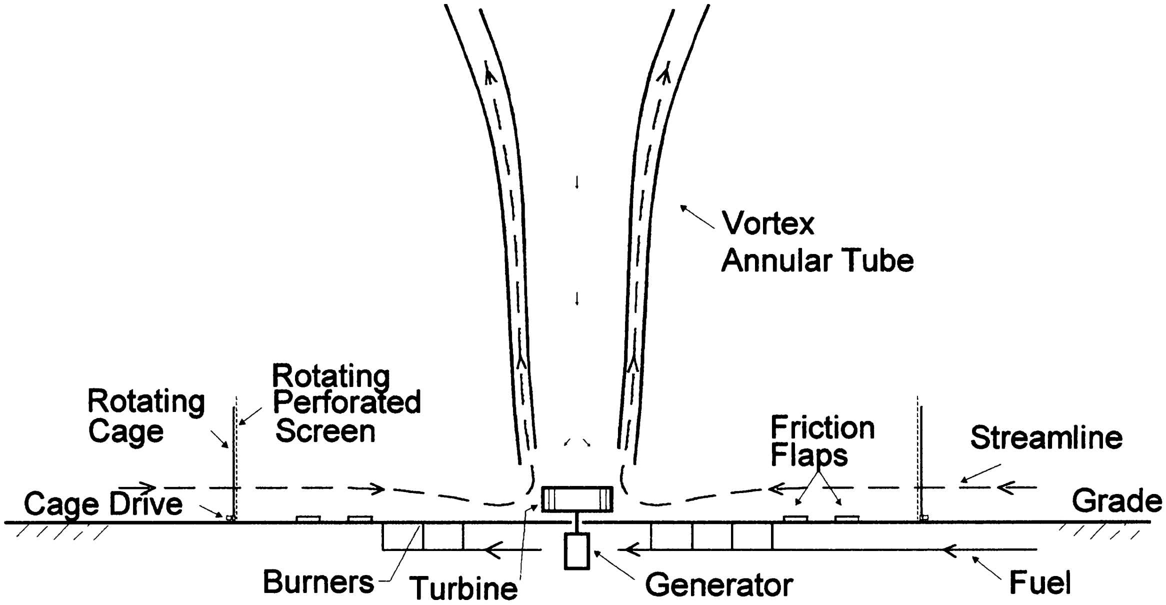

Fig. 1. Atmospheric vortex engine concept (adapted from [2]).

vective available potential energy, the most important factor in the convective vortices systems as the measure of convective instability) for the first time and also includes vortex maintenance factor, f_m, which are main novelties comparing previous research of other authors. Hence, the major finding is the proof of the analytical connection between previously mentioned terms and pressure potential. The proposed analytical approach is also validated with available experimental data from the literature, and gained results are in agreement with field observation data.

2. THEORY

As previously mentioned in the introduction section, convective vortices can be conceptualised as reversible heat engines. Therefore, researchers need to use a heat engine framework to develop a theoretical approach to them, as found in [11, 14–17]. Following the example of Renno [13], a schematic overview of a convective circulation system is shown in Fig. 2. Several important points are labelled in Fig. 2. Point “a” is a point outside the radius of influence of the vortex, point “b” is in the region of the maximum tangential air velocity, point “c” is a stagnation point in the centre of the convective vortex and point “d” is at the top of the convective circulation system. These labelled points are used in the subsequent thermodynamic analysis and analytical modelling.

If we assume a steady state, then the energy balance equation for the flow process, derived from the first law of thermodynamics, can be written as follows:

$$\oint dq = \oint dh_{\text{tot in out}} - \oint v dp = \oint dw_{mt} + \oint dw_{sh}, \tag{1}$$

where the total (stagnant) enthalpy can be expressed as follows:

$$dh_{\text{tot in out}} = dh + de_k + de_p \ . \tag{2}$$

In Eq. (2), dh is the specific enthalpy of the air, which includes the latent heat of vaporisation; de_k is the change in kinetic energy; and de_p is the change in potential energy, v is specific volume of air, w_{mt} specific

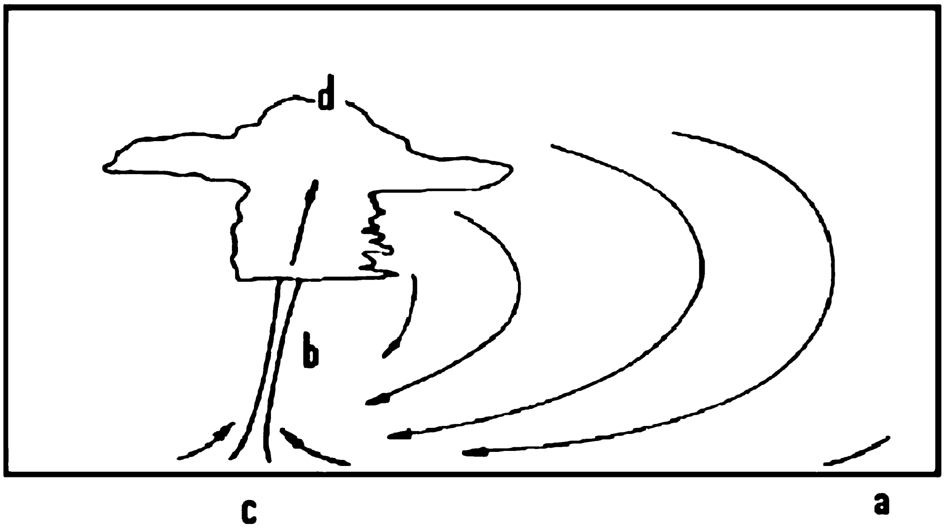

Fig. 2. Sketch of the convective vortex circulations (adapted from [14]).

available work for maintenance of the convective vortices, w_{sh} specific useful mechanical (shaft) work and q specific heat input into convective vortices system. Eq. (1) shows that part of the heat input into the convective system is spent on maintaining the convective vortices in the surrounding atmosphere, and the other part is available for potentially useful work, called the shaft work. The overall work in the convective circulation can be written as follows:

$$\oint dw_{mt} + \oint dw_{sh} = - \oint dF_R, \tag{3}$$

where dF_R is the energy loss due to friction. Part of the friction loss is used to maintain the convective vortices and the rest of it is the available shaft work. Additionally, it is assumed that most of the heat input is used to maintain the convective vortices (frictional and dissipation work in the surrounding atmosphere) and that just a small part of it is available as useful work (diffusion term was not analysed in detail in this paper, however work on it is indirectly included in the maintenance work of the convective vortices system). For example, if we consider natural vortices, the available work is the ’“destruction work” that creates hazards and cannot be used. On the other hand, if we manage to produce and control convective vortices, the available part of the overall work in the convective vortices circulation system could be directed and used for electricity production through a turbine assembly (as previously mentioned in the introduction section).

Heat input into a convective vortices circulation system is ensured from the surroundings, although other available heat sources could be used (e.g., waste industrial heat). The surface heat flux consists of convective heat flux from the ground to the air flow and of heat generated from friction with the ground when air passes from point *a* to the vortex centre. There is also radiative heat flux from the ground to the surroundings that causes a decrease of the specific enthalpy difference (heat loss into the surroundings) and the heat flux due to increase of the absolute humidity of the air flow from the point *a* to the vortex centre (latent heat flux). The general heat balance from the ground to the air flow can be written as follows:

$$dh_{\text{tot in out}} = dq_{\text{convection}} + dq_{\text{latent}} + dw_{\text{friction}} - dq_{\text{radiation}}, \tag{4}$$

where total enthalpy, $dh_{\text{tot in out}}$, includes heat flux due to convection, $dq_{\text{convection}}$, due to vaporisation, dq_{latent}, due to parcel friction, dw_{friction} and heat loss into the surroundings due to heat radiation. Depending on the surrounding conditions, the total (stagnant) enthalpy difference for natural convective vortices systems ranges from $\Delta h_{\text{tot in out}} = 16{,}000$ to 40,000 J/kg, as mentioned in [14]. As Fig. 2 shows, this enthalpy difference is the heat difference between points *a* and *c*. The influence of the absolute humidity of the air on the temperature difference achieved can be estimated as follows:

$$\Delta(\Delta T) = \frac{r}{c_p}\Delta x, \tag{5}$$

where r represents the latent heat of the vaporisation, Δx humidity perturbations and c_p specific heat capacity of air. In general, an increase in the absolute humidity of the convective vortices system clearly increases the difference in air temperature. (It is possible that a decrease in air temperature could only be expected when water is added to the system.) Typical humidity perturbations in natural convective vortices range from $\Delta x = 0$ kg/kg for dust devils to 0.002 to 0.005 kg/kg for waterspouts and approximately 0.01 kg/kg for tornadoes and hurricanes [14, 17, 18]. From these values, it is clear that the humidity of the air flow in the convective vortices system is an influential parameter in the magnitude of the convective vortices.

Renno et al. [15] analysed the influence of the convective available potential energy (CAPE) value on convective vortices and found that the CAPE value could be connected to the intensity of a convective vortices system, i.e., with instability of the convective heat exchange. Another thermodynamic analysis regarding the physical aspects of the CAPE value and TCAPE (total CAPE is as defined in [15]), can be found in [19].

Temperature increase in general causes increase of the CAPE value, but the most important parameter that affects the CAPE value is air humidity. Strongest natural convective vortices as hurricanes or tornadoes have high humidity perturbations, and as a consequence they also have high CAPE values or intense convective updrafts. Furthermore, based on the approach introduced in [13] for a convective vortices system, the following expression for CAPE follows:

$$\oint dw_{mt} + \oint dw_{sh} = \text{CAPE}. \tag{6}$$

Therefore, according to the proposed approach, the CAPE value is the part of the overall heat input into the system that is used to maintain the convective vortices and the part that is available for useful work and corresponds with, $\text{CAPE} = -\oint dF_R$ as it is the case in Eq. (3). Hence, from two different aspects we get very important equality. From that perspective, the maintenance factor of the convective vortices in [13] is introduced and defined as follows:

$$f_m = \frac{w_{mt}}{\text{CAPE}}. \tag{7}$$

where f_m represents vortex maintenance factor. A higher f_m value means a smaller quantity of available shaft work that can be used to produce electricity. The maintenance factor is important because it allows determination of the quantity of specific work that would be spent on maintenance of the convective vortices and part of the specific work that could be available for useful shaft work. According to the approach proposed in [13], the ratio of heat to work efficiency of a convective vortex heat engine, η_{vs}, can be defined as follows:

$$\eta_{vs} = \frac{w_{sh}}{\Delta h_{\text{tot in out}}} = \frac{\text{CAPE} - w_{mt}}{\Delta h_{\text{tot in out}}} = \frac{\text{CAPE}\cdot(1-f_m)}{\Delta h_{\text{tot in out}}}, \tag{8}$$

where enthalpy difference can be expressed as,

$$\Delta h_{\text{tot in out}} = \frac{\text{CAPE}\cdot(1-f_m)}{\eta_{vs}}. \tag{9}$$

Equation (8) gives the efficiency of a convective vortex heat engine, which dictates the available useful shaft work that can be extracted from a convective vortices system. The magnitude of the maintenance factor

f_m is expected to be relatively high in the case of natural vortices, which is confirmed in the next section. Assuming $f_m = 0.9$, a CAPE value of 2,000 J/kg and a typical value of 25,000 J/kg for the specific enthalpy, the heat-to-work efficiency has a value of $\eta_{vs} = 0.08$, which is consistent with the ranges of values for typical natural convective vortices reported in [14, 20]. For the previous calculations, the value of the maintenance factor was taken to be $f_m = 0$ so that the calculated value for η_{vs} could be compared with the available data in [14, 20], wheren convective vortices were not used as possible sources of useful mechanical work. This maintenance factor was chosen because the possible utilisation of convective vortices as heat engines was not analysed; in other words, all of the work produced from the heat input is used to maintain the convective vortices in the surrounding atmosphere, which is a case for which $f_m = 0$. It is thus clear that Eq. (8) could be used to estimate the thermodynamic efficiency of convective vortices as heat engines and evaluate technical concepts that utilise convective vortices.

Furthermore, if we assume a dry adiabatic air updraft (it could be assumed in the case of convective vortices that are similar to dust devils or non-precipitating tornadoes where humidity perturbations are negligible so there is no influence of water vapour on specific heat capacity) and combine this assumption with Eq. (8) it yields to the following expression:

$$\int dh_{\text{tot in out}} = -\int v\,dp = \Delta h_{\text{tot in out}} = \frac{\text{CAPE}\cdot(1-f_m)}{\eta_{vs}}, \tag{10}$$

where, equality, $\int dh_{\text{tot in out}} = -\int v\,dp$ follows from the first law of the thermodynamics. Hence, if we connect Eq. (9) which is derived directly from the general definition of the efficiency, with Eq. (10), derived from the energy balance equation, we obtain the following equation in the case of air as an ideal gas:

$$-\int RT\,\frac{dp}{p} = \Delta h_{\text{tot in out}} = \frac{\text{CAPE}\cdot(1-f_m)}{\eta_{vs}}, \tag{11}$$

where, R represents ideal gas constant for the air, T temperature of the air and p pressure. Finally, by integration from of Eq. (11), we can obtain the necessary pressure difference between the surroundings p_a and a point inside convective vortices p_b (where the tangential air velocities are maximal in magnitude),

$$\frac{p_b}{p_a} = \exp\left(-\frac{1}{R^a\bar{T}^b}\cdot\frac{\text{CAPE}\cdot(1-f_m)}{\eta_{vs}}\right), \tag{12}$$

where ${}^a\bar{T}^b$ is the mean air surface temperature between the points a and b in Fig. 2. The derived pressure ratio Eq. (12) is important to determine the pressure potential as the function of the CAPE value (as the total energy input into the convective system) and as the function of the maintenance factor which determines possible amount of the useful mechanical work.

According to Renno [14] and Souza et al. [20], the thermodynamic efficiency of convective vortices can be approximated as a function of the depth of the convective boundary layer, Z, and the temperature of the hot reservoir, T_h (g represents acceleration of gravity),

$$\eta \approx \frac{gZ}{c_p T_h}, \tag{13}$$

where thermodynamic efficiency in Eq. (13) corresponds to the one defined in Eq. (8), i.e., $\eta \equiv \eta_{vs}$. Previous Eq. (13) is valid for convective systems were heat transfer by heat convection is much greater than heat transfer by heat conduction. According to the observations [14] it is shown that higher thermodynamic efficiency could be expected in the case of the non-precipitating convective vortices.

The Carnot thermodynamic efficiency, with a maximum value of 1.0, can also be defined as a function of the ambient temperature lapse rate Γ_a as follows:

$$\eta_C \approx \frac{\Gamma_a\, Z}{2T_h}, \tag{14}$$

where according to [14], factor 2 in denominator results from the assumption that the atmospheric slab radiates at the mean temperature of the convective layer, which is assumed to be at 1/2 the distance between the surface and the top of the convective layer. This assumption was validated in [20].

Then, the pressure ratio defined in Eq. (12) can be further modified as follows:

$$\frac{p_b}{p_a} = \exp\left(-\frac{1}{R^a \bar{T}^b} \cdot \frac{\mathrm{CAPE} \cdot (1 - f_m) \cdot c_p\, T_h}{g \cdot Z}\right). \tag{15}$$

Finally, an analytical expression for the pressure difference between the surroundings and the points inside convective vortices (points a and b in Fig. 2) can be established as follows:

$$\Delta p_{a-b} = p_a \cdot \left[1 - \exp\left(-\frac{1}{R^a \bar{T}^b} \cdot \frac{\mathrm{CAPE} \cdot (1 - f_m) \cdot c_p\, T_h}{g \cdot Z}\right)\right]. \tag{16}$$

Equation (16) relates important parameters that influence the pressure difference, making the equation derived useful in estimating the pressure difference gained in the convective vortex and therefore the magnitude of the vortex. The important innovation in this proposed approach is the analytical identification of the well-known CAPE value and the maintenance factor of the convective vortices f_m as influential parameters of the magnitude of the pressure potential. In the subsequent sections of this paper, Eq. (16) will be tested and validated with available field data and with research results from other authors.

3. VALIDATION AND COMPARISON WITH AVAILABLE FIELD DATA

If we compare the general characteristics of convective vortices in previously proposed concepts [1, 6] with natural ones, the previous designs are most similar to dust devils in terms of general behaviour, genesis, structure and intensity. Available field data for dust devils can be found in the research papers of Sinclair [21–23], who observed dust devils in desert areas and in papers by other researchers [24–28]. According to the field data, the average pressure potential for dust devils ranges from 2.0 to 5.0 hPa. For the specific dust devil that Sinclair observed [21–23], the measured pressure potential was $\Delta p_{a-b} \approx 2.0$–$3.0$ hPa, the surface pressure at the site was $p_a \approx 925$ hPa, the depth of the convective layer was approximately $Z \approx 3$ km, and the temperatures at points a and b were $T_a \approx 319$ K and $T_b \approx 324$ K, respectively. The pressure potential, according to Sinclair's previous field data, was $\Delta p_{a-b} \approx 3.0$ hPa. Furthermore, according to Ninic [29], the CAPE value for developed tornadoes ranges from 1,000 to 6,000 J/kg; therefore, for dust devils, which are the weakest of natural convective vortices, the CAPE value is expected to be in the range of 1,000 to 2,000 J/kg. If we calculate the pressure potential from Eq. (16) with a CAPE value equal to 1,400 J/kg and $f_m = 0.98$, we obtain a pressure potential of $\Delta p_{a-b} = 3.1$ hPa, which is consistent with the value Sinclair observed [23].

Renno in [14] calculated pressure potential range in the case of natural convective vortices. Hence, this data for the pressure potential is compared to the data calculated by the herein proposed analytical approach and values are shown in Table 1. Average values for CAPE and for the depth of the convective boundary layer are set regarding the types of natural convective vortices. It is obvious that calculated data for the pressure potential are in agreement with the data calculated by Renno in [14] where maintenance factor ranges from 0.5 to 0.99.

Table 1. Data comparison for the pressure potential.

			Calculated	Calculated, Ref. [13]
	CAPE (J/kg)	Z (km)	Δp_{a-b} (hPa)	Δp_{a-b} (hPa)
Dust devils	1,200	1	3.62	2–5
Weak waterspouts	2,000	3	4.5	3–6
Strong water spouts	2,600	5	42.5	30–60
Tonadoes	4,000	8	64.95	50–100
Hurricanes	5,000	10	81.45	60–120

Table 2. Data comparison for the pressure drop between observed values and calculated.

		Observed	Calculated
Day	CAPE (J/kg)	Δp_{a-b} (h Pa)	Δp_{a-b} (hPa)
14	1,200	2.1	1.99
15	600	0.8	0.88
16	1,000	1.6	1.66
17	1,100	1.8	1.82
18	2,400	2.3	2.32
19	400	0.6	0.66
20	700	1.1	1.16
21	1,500	2.4	2.49
22	1,000	1.7	1.66
23	2,600	4.4	4.32

Souza et al. [20] also provided observation data for the pressure drop between the forest and pasture sites and we have also compared this data with the data calculated by the proposed analytical approach. Comparison results are presented in Table 2, and agreement is established were CAPE value ranges from 400 up to 2,400 J/kg which is an expected value range that can be found in nature, i.e., in the case of the convective circulation in the atmosphere.

Furthermore, if the CAPE value and maintenance factor f_m are varied, we obtain some interesting results that are shown in Fig. 3.

First, it is interesting that for a range of the CAPE value between 1,200 J/kg and 1,800 J/kg, we obtain a pressure drop potential that ranges from 2.5 to 4.0 hPa ($f_m = 0.98$), which is in agreement with the field data and with research results obtained by other authors [14, 17, 22, 23]. (Note that, as previously mentioned, the pressure difference is expected to range from 2.0 to 5.0 hPa.) If we select $f_m = 1.0$, the proposed model is not valid. This is logical because friction with the ground is necessary for vortex genesis and maintenance, so this shows that convective vortices must have available useful work in addition to maintenance work, which is the destruction work of convective vortices. This conclusion is very important because it proves that a system with convective vortices can deliver a certain amount of useful mechanical work. The magnitude of the introduced factor f_m is shown to be high (although it could range from 0 to 1.0), which leads to the conclusion that a relatively small amount of useful mechanical work is available from the convective vortices system. Although the value of the factor is high, the potential for mechanical work production is very large because of the large heat input into the convective vortices system and because electricity could be produced renewably. Finally it can be concluded that the proposed analytical model is successfully validated by the available experimental data observed in the field and that the calculated pressure difference is in the expected range, reported by other researchers. It is also important to emphasize that focus of this paper was not a specific convective vortex power plant, hence this model was verified according to the available observation data, i.e. there was no possibility to analyse specific constructional parameters on the

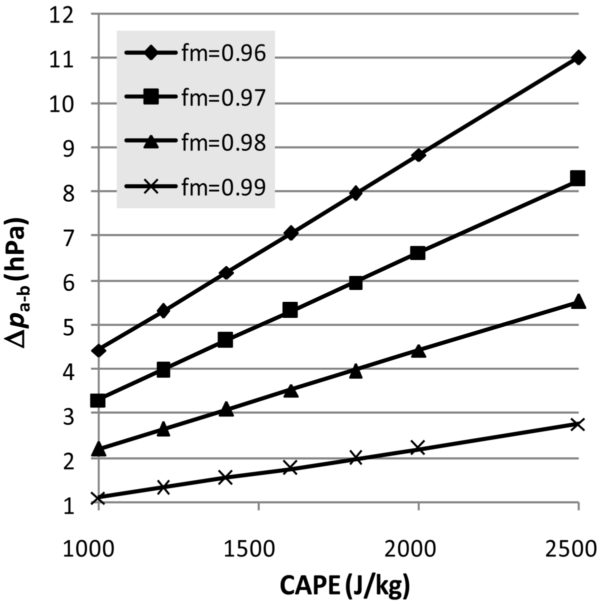

Fig. 3. Pressure difference potential as a function of the CAPE value and f_m.

magnitude of the pressure potential. The main goal of the paper was to derive an analytical model which connects CAPE value with pressure potential.

4. POTENTIAL FOR THE APPLICATION

The analytical approach derived in this paper can be useful in estimating the pressure drop potential in designs that use convective vortices as heat engines. It is also shown in this manuscript that there is potential use of the developed analytical approach in the case of the pressure potential analysis for meteorological purposes. The magnitudes of convective vortices can also be estimated using the proposed approach because, in general, stronger convective vortices have a higher pressure potential, which corresponds to a higher amount of available work. Furthermore, the increased pressure potential is important because we can estimate the quantity of the available mechanical shaft work that could be extracted from a convective vortices system. The contribution to the theoretical research on designs in which convective vortices act as heat engines is also established because all of the important and influential parameters for the pressure potential of convective vortices are now connected through an analytical expression that has been validated with field data. Developed analytical model could also be used for meteorological purposes, i.e. in the case of natural convective vortices.

5. CONCLUSIONS

The development of new green alternative energy technologies is necessary to ensure that future energy demands are met, especially for solar energy, from which carbon-free electricity could be produced. Because of these future demands, research on alternative energy technologies is crucial. In this paper, an analytical approach is proposed for the estimation of the pressure potential of convective vortices as heat engines, with application to the research regarding the concepts that utilise convective vortices as heat engines. The novel results of the proposed approach are that the well-known CAPE value and frictional factor f_m are now analytically related and it is shown that they have significant influences on the magnitude of the pressure potential of the convective vortices system. The physical aspect of the frictional factor f_m is interesting because it indirectly shows how much of the work can be extracted from a convective vortices system as available mechanical shaft work without the physical destruction of the convective vortices. This conclusion is based on the calculated pressure difference potential range. In the case of natural vortices, the calculated values for the pressure potential are in agreement with observed values when natural vortices are established in the surrounding atmosphere. It could also be concluded from the results that when convective vortex systems are used as heat engines, they can deliver a relatively small amount of useful mechanical shaft work but, most importantly, they can produce electricity renewably. However, proposed model should be used for the estimation of the pressure potential in the case of the vortex power station, where all influential and technical parameters are defined. Finally, it can be concluded that the proposed analytical approach for the estimation of the pressure potential contributes to the theoretical research on the concepts that use convective vortices as heat engines because all of the important and influential parameters for the pressure potential of such convective vortices are now related through an analytical expression that has been validated with field data. Therefore, the proposed analytical approach could be used to validate the technical concepts that use convective vortices as possible sources of mechanical work.

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