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EXPERIMENTAL EVALUATION OF A SMALL SOLAR UPDRAFT TOWER

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Abstract. *The growing world demand for energy and concerns about the environmental impacts of energy production have motivated research into alternative sources of energy. In this context, solar updraft towers arise as a promising device that use solar radiation to generate a flow of heated air. The hot airflow generated can be used to produce electric power or to dry agricultural products. In this paper, experimental data from a small-scale prototype of a solar updraft tower were evaluated. The prototype was built in the city of Belo Horizonte/Brazil, in a scale 1:50 of the Manzanares prototype, with 5m in diameter and 2,5m height. Temperature and relative humidity were measured inside the prototype, allowing the assessment of the thermal insulation of the tower, temperature distribution in the collector and water removal from the ground.*

Keywords: *Solar updraft tower, Prototype, Experimental analysis*

1. INTRODUCTION

The concept of solar updraft tower (also called solar chimney) was developed by Cabanyes in 1903, but only in 1968 professor Jörg Schlaich described it, making possible its use. In 1981, the German Ministry of Research and Technology, in partnership with Unión Fenosa, promoted and financed the construction of the first prototype of solar updraft tower with a maximum power of 50 kW in the Manzanares desert, 150 km south of Madrid (BERNARDES ET AL., 2003), Fig.1. The working principle of solar updraft towers can be described as the combination of technologies of solar collectors, chimneys and turbines. Part of the solar radiation that reaches the device goes through the collector and promotes the heating of the ground. The heated ground transfers heat by natural convection to the mass of air inside the collector, which in turn flows upwards towards the chimney due to buyoancy forces caused by temperature gradients (SCHLAICH, 1995).

Figure 1. Solar updraft tower in Manzanares - Spain

Among the advantages of the use of solar updraft towers are the use of both direct and diffuse components of solar radiation, and the ability of continuous operation, due to the fact that part of the stored energy in the ground during the day is released during the night to the airflow. It is a simple technology and the building materials, mainly steel, concrete and glass, are widely available. Construction sites can be desert areas. It is accessible to almost every country. It has low maintenance costs, simple operation and durability. Its environmental impact is low for the entire life cycle including construction, operation and deactivation. Its power and efficiency increase with its size, while the cost of energy production is reduced (ZHOU AND XU, 2015).

The installation of Manzanares was carried out during a period of seven years, during which several tests were carried out and measurements of velocity, temperature and solar radiation were performed inside the device and in the external environment (SCHLAICH, 1995). The prototype installed in Manzanares has a chimney with 194.6 m of height and 10.16 m of diameter (Figure 1). The collector has an average radius of 122.0 m and an average height of 1.85 m in relation to the ground. The prototype has a turbine with four blades of 5 m, with a maximum power of 50 kW. The plant operated from 1982 to 1989, and was connected to the local network between 1986 and 1989 (SCHLAICH, 1995). The operation and results of the prototype performance tests are described by Haaf et al. (1983, 1984), where the feasibility and reliability of the project were demonstrated.

Since the construction of the Manzanares prototype, several studies have been carried out, both in numerical analysis and in experimental and theoretical analysis. Since 1997, small prototypes have been built in several countries, such as Botswana, Brazil, China, the United States of America, Iraq, Iran, Jordan, Portugal, Turkey, among others. Among them, stand the works of Pasurmarthi and Sheriff (1997), Cebeci et al. (2005), Zhou et al. (2007), Kethogetswe et al. (2008), Maia et al. (2009), Ibrahim (2009), Üçgül and Koyun (2011), Sabah and Miqdam (2011), Kasaeian et al. (2011), Al-Dabbas (2011), Mohammad and Obada (2012) and Najmi et al. (2012).

The main objective of this paper is to experimentally evaluate the performance of a small prototype of a solar updraft power plant. Temperature and relative humidity were measured inside the device, and the removal of water from the ground, the distribution of heat in the collector and the thermal insulation of the tower were assessed.

2. EXPERIMENTAL METHODOLOGY

The device was built at Pontifícia Universidade Católica de Minas Gerais, PUC Minas. Before the installation of the device, the land was cleaned through weeding and the construction of a concrete base to receive the solar updraft tower. The ground for the construction and installation of the solar updraft tower should prevent the water present in the ground from migrating to the interior of the device. Therefore, it was applied a waterproof acrylic blanket in two black cross-layers to avoid the passage of moisture from the ground to the interior of the device and increase the rate of absorption of solar radiation.

The tower is 2.5 m in length and 200 mm in diameter was built using polyvinyl chloride (PVC) pipes, to ensure a light and resistant structure. Moreover, PVD presents an excellent cost-benefit ratio when compared to materials such as wood and metals, as well as advantages such as thermal insulation, ease of installation, low maintenance and low roughness.

The solar collector covers an area of approximately 20 m², and height in relation to the ground of 10 cm. The support structure was made up of L-shaped aluminum profiles to form polygons which were then screwed together with 3/16 bolts and nuts. The polygons formed by the profiles were screwed to the threaded rods, keeping the system stable. The thermal film used on the cover was chemically added with an infrared radiation blocking agent and a long-acting ultraviolet stabilizer. The prototype is shown in Fig. 2.

Figure 2 – Prototype of solar updraft tower

Measurements for temperature distribution inside the device were performed by six INSTRUTHERM K-type thermocouples, with mineral insulation, AISI 304 steel sheath, 3 mm in diameter (Fig. 3). The above-mentioned thermocouples have a calibration certificate with an uncertainty of ± 0.58 ° C (manufacturer's data).

The DHT11 sensor, Figure 3, was used to measure temperature and relative humidity at the inlet and outlet of the device. It allows to measure temperatures between 0 and 50°C and relative humidity (RH) in the range of 20 to 90%. Its precision range is 2° C and 5% RH, with uncertainties of ± 0.2°C and ± 1% RH (manufacturer's data).

For the acquisition of the signals, Arduino Uno was used, which is a microcontroller board, a Base Board that acts as the motherboard of the system and, together with the other items, the Nanoshield Thermocouple was used to read temperatures from -270ºC to 1372ºC with 0.25° C resolution using a K-type thermocouple sensor. The signal was then treated in LabVIEW®.

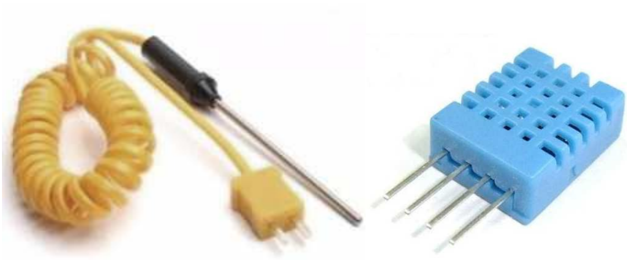

Figure 3. Thermocouple type K and Thermo-hygrometer (DHT11)

Table 1 presents the uncertainties of the measurements, obtained using EES® commercial software.

Table 1 - Propagation of uncertainties

Sensor	Number	Uncertainties		
		Temperature [±°C]	Relative humidity [±%u.r.]	Absolute humidity [±g/m³]
Thermo-hygrometer	144064	0,20	1,00	1,07
	144065	0,20	1,00	1,08
Thermocouple type K	144067	2,89	-	-
	144068	1,52	-	-
	144069	2,29	-	-
	144070	1,66	-	-
	144071	2,24	-	-
	144072	2,43	-	-

For the effects of varying the intensity of solar radiation during the day and the storage of heat by the ground at night, the duration of each test could not be less than one complete daily cycle (24 hours). The relative humidity was measured through thermo-hygrometers installed at the collector inlet (inlet relative humidity) and at the tower outlet (outlet relative humidity). Firstly, the removal of water from the ground was evaluated. This parameter is important because it is one of the factors that most contribute to the reduction of the exergetic efficiency of the system (Maia et al, 2013).

After the construction of the prototype, it was necessary to know the temperature distribution in the collector, therefore, two similar tests were performed, varying only the angular position in which the sensors were placed (aligned to the north and the east). The positioning of the sensors inside the solar updraft towers was determined to achieve an approximately constant spacing along the collector. In the measurement of flow parameters inside the collector, the sensors were held at a position corresponding to half the height of the collector.

In order to evaluate the thermal insulation of the tower, three thermocouples were installed along the height of the tower, maintained on the axis of symmetry. The distribution of temperature was evaluated for two different conditions: the tower without thermal insulation and the tower with glass wool.

3. RESULTS AND DISCUSSIONS

The evaluation of the thermal insulation of the PVC tower is shown in Figures 4 and 5. Figure 4 presents the distribution of temperatures along the axis of symmetry, for the PVC tube without thermal insulation. The thermocouples were placed at heights of 1.0 m, 1.5 m and 2.0 m in relation to the ground surface. It is possible to observe that, during the night, the temperature varied up to 12 °C from 1.0 m to 2.0 m of length, which shows that an adiabatic tower hypothesis cannot be assumed. This condition is not suitable, since a lot of heat is being wasted to the external environment.

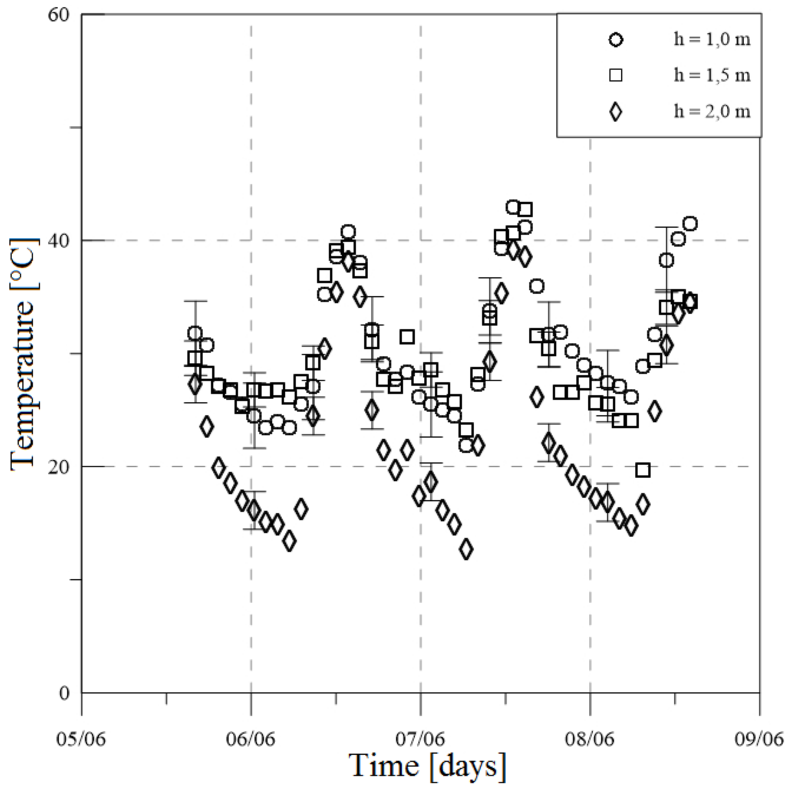

Figure 4. PVC tower

As a solution, insulation with glass wool was added to the PVC, and the results are shown in Figure 5. It can be seen that the thermal insulation allowed a maximum drop in temperature of 1.5 °C. This value is within the uncertainty of the thermocouples, which makes possible to assume a hypothesis of adiabatic tower.

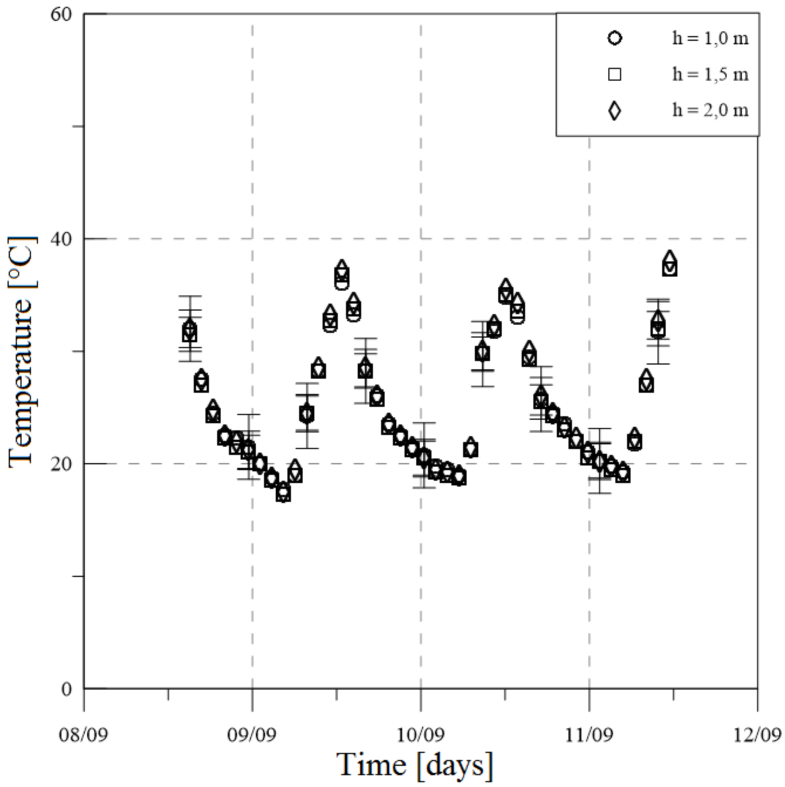

Figure 5. PVC tower with glass wool

The relative humidity of the airflow was measured at both the inlet and outlet of the device. By comparing the absolute humidity, it is possible to evaluate if the airflow is removing water from the ground. During the tests, the humidity varied throughout in a range of 18% to 97%, as shown in Figure 6. In general, the relative humidity increases when the ambient temperature decreases. Since the air is heated from the inlet to the outlet, the relative humidity at the outlet is always lower than the relative humidity at the outlet.

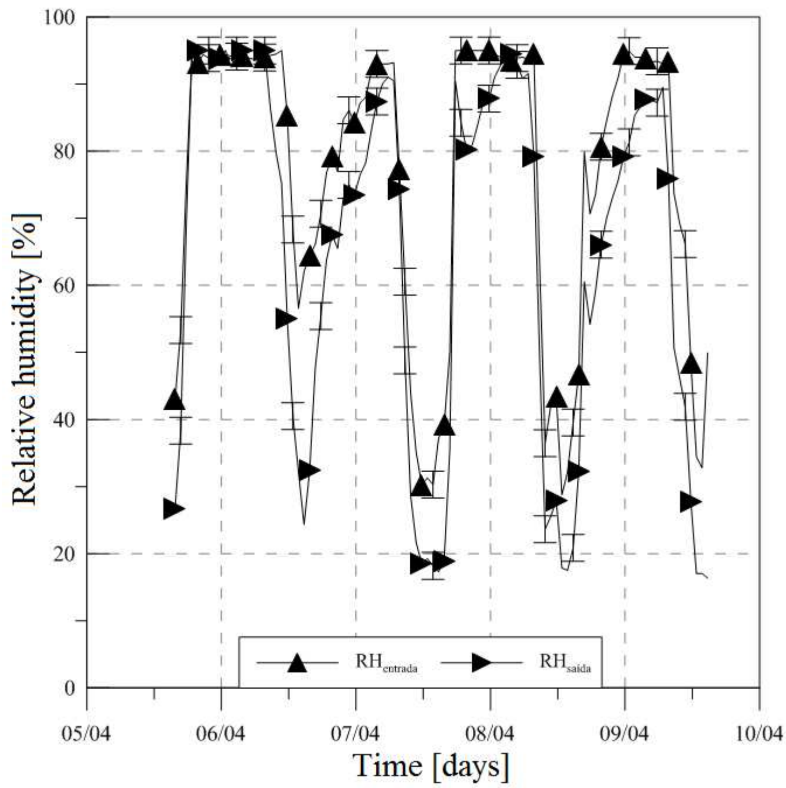

Figure 6. Relative humidity

In order to evaluate the amount of water removed from the ground by the airflow, it is necessary to determine the absolute humidity (Figure 7). The average variation between the absolute humidity from the inlet to the outlet was 0.72 g/m³. The maximum absolute humidity found during the tests was 25.4 g/ m³ and the minimum value was 10.25 g/m³. Taking as reference the values obtained by the average variation of the absolute humidity it is possible to assume that the amount of water removed from the ground was low, and the soil can be considered as impermeable. This is an important parameter to be evaluated, since small solar updraft towers can be used to dry agricultural products. If the airflow removes a great amount of water from the ground, the relative humidity of the air increases, and the difference between the relative humidities of the ground and the products to be dried decreases, and the efficiency of the drying process decreases.

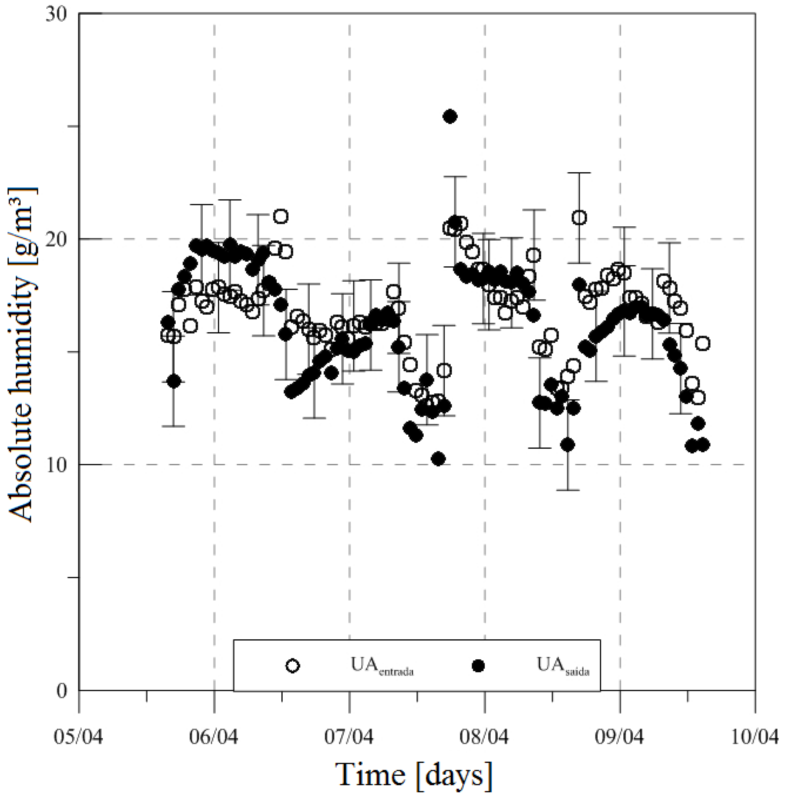

Figure 7. Absolute humidity

Figures 8 and 9 present the results for the temperature distribution along the collector. Two tests were performed, one with the thermocouples aligned to the north and the other with the thermocouples aligned to the east. It can be seen that, as expected, the airflow is heated towards the symmetry axis. The values indicated in the figures represent the distance from the symmetry axis, which means that r = 2.5 m represents the inlet airflow temperature.

It can be also noted that the temperature inside the collector follows the behavior of the incident solar radiation, increasing from the morning to noon and decreasing after that. In general, the average temperature variation between the collector inlet and the point near the center of the measured device, 0.5m, was 1.81°C when the thermocouples were aligned to the north and 0.68°C when the thermocouples were aligned to the east. The maximum temperature variation between the edge of the collector and the point near the center of the device was 9.5°C for the thermocouples aligned to the north and 7.75°C when aligned to the east. Although the tests were performed on different days, one hypotheses raised for the fact that the north-oriented sensors presented lower temperatures is related to the fact that the data were obtained on a windy day. The device was built in a region between buildings being unobstructed only the north face of the prototype subject to the influence of winds. It is important to mention that the incident solar radiation was similar for both days.

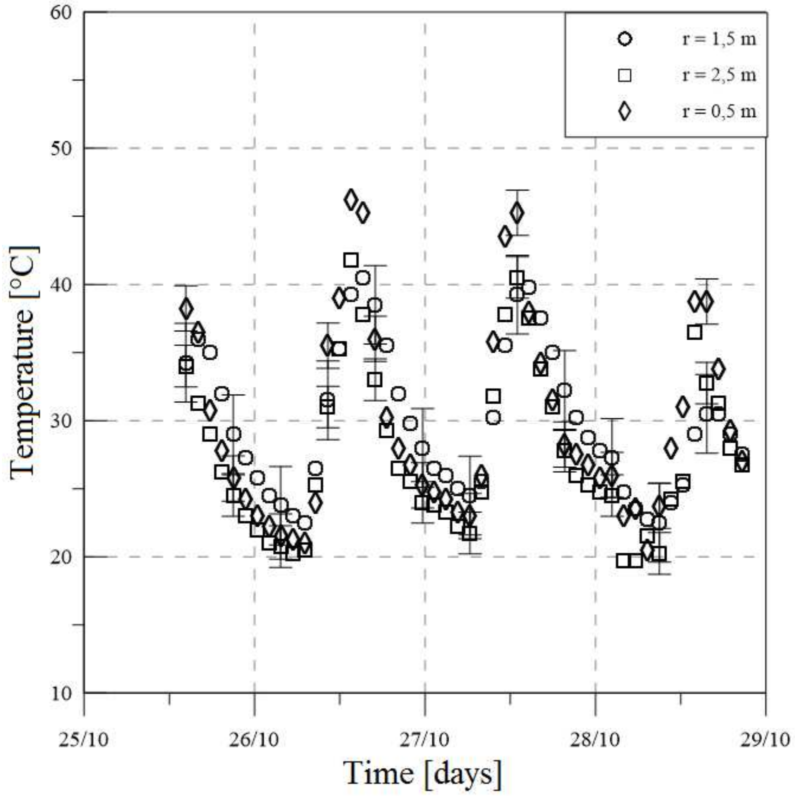

Figure 8. Aligned east

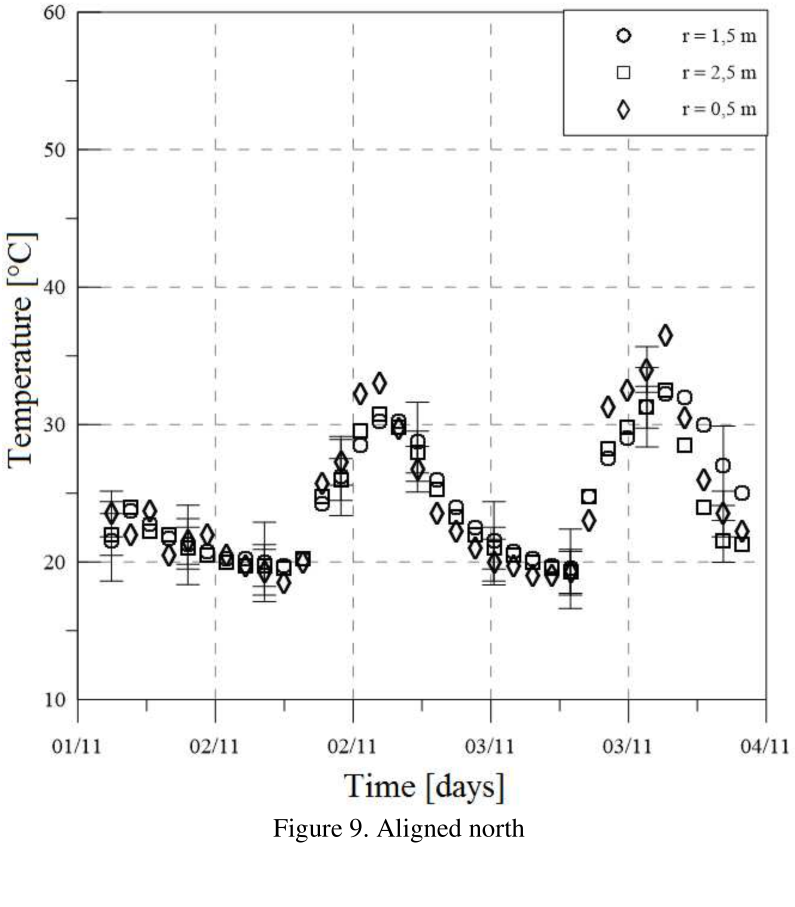

Figure 9. Aligned north

4. CONCLUSIONS

After designing and constructing a small scale solar updraft tower prototype, the temperature and humidity readings were performed for some specific collector and tower locations, varying some parameters on different days. The tests indicated that it is necessary to use a thermal insulation on the PVC tube, in order to avoid heat losses for the ambient environment, especially at night. The preparation used on the soil was suitable to decrease the removal of water from the ground by the airflow, since, on average, the variation between the inlet and outlet absolute humidity was 0.72 g/m³. The influence of the albedo on the temperature distribution was significant, since the crosswind caused differences on the temperatures distribution in the collector along north and east directions, even for similar solar radiation conditions.

5. ACKNOWLEDGEMENTS

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