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An experimental study on the transient thermal response of an electronic equipment box for UAV remote sensing applications

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Abstract. An experimental study of the transient thermal characteristics of an electronic equipment box is presented. The box is designed to house devices typically used for UAV-based remote sensing applications. Different cooling systems, aimed at maintaining all the components within their allowable temperature limits for the duration (15-20 min) of each UAV flight, have been considered. They include forced convection of external or internal air and use of storage units (cold gel packs) inside the box. Experiments indicated that a mixed active/passive technique consisting in the combination of cold gel packs and internal ventilation, without any air renewal, provides the most suitable cooling condition.

1. Introduction

The increasing developments and improvements of Unmanned Aerial Vehicles (UAVs) provide excellent opportunities for remote sensing in different technological fields. Visible, near-infrared, and thermal cameras, multispectral and hyperspectral sensors, and laser scanners are typical instruments installed onboard of such platforms [1]. For practical reasons (e.g., replacement of sensors or data storage units, protection against the atmospheric agents), it could be advisable to accommodate these sensors inside a box mounted underneath the drone, as shown in fig.1.

Due to the heat generated by the sensors during their operation, the efficient cooling of the box interior is required to ensure satisfactory performance and reliability of electronics; moreover, the additional thermal load from the sun must be taken into account. The cooling system has to be suitable for light-weight aerial remote sensing, without significant increases in mass and volume. Since rotary-wing UAV systems exhibit flight times typically less than 30 min work [2], the thermal control of the box interior has to be guaranteed only within a restricted time interval (e.g., 15−20 min). Therefore, complex and/or heavy and/or expensive cooling systems such as heat sinks, heat pipes or jet impingement, typically designed to provide long-term thermal control of electronics, are not strictly necessary and, at the same time, may not fulfil the payload requirement of commercial, light UAVs.

The cooling techniques can be classified as active and passive methods. The passive schemes do not need any external power, while active schemes (i.e., using fans or blowers) require external power to dissipate the heat from the electronic devices. Among the active methods, the forced air cooling is frequently used for electronic equipment; due to the greater and greater complexity of electronics, the cooling system based on air-moving devices has to be carefully designed [3−7]. Among the passive methods, air free convection and radiation cooling are often not sufficient to comply with the heat dissipation requirement, while the thermal control in transient conditions could take advantage of phase change or heat storage materials to reduce temperature oscillations of electronics [8−10] or to keep, for a given time interval, some items or devices at a relatively low temperature [11, 12].

In the present work, experiments have been performed to investigate the transient thermal response of a box containing electronic equipment, with the purpose of identifying the most suitable cooling condition. Due to the large variety of devices employed in UAV-based remote sensing systems, the search for the best cooling solution of the electronic equipment box cannot be pursued and generalized for any assembly of sensor devices; for this reason, only one specific component is under consideration in this experimental investigation and its thermal control in dynamic conditions has been addressed according to different cooling solutions. A more exhaustive and complete presentation of experiments, as well as their comparative analysis with results obtained by a lumped-parameter theoretical model, developed in support of the experimental work, is provided in [13].

Figure 1. UAV with a box containing devices for remote sensing applications.

2. Experimental setup and procedures

The experimental test section is shown in the photograph of fig.2 and schematically depicted in fig.3. The thermal source, simulating an electronic device, consists of an aluminum plate, with dimensions of 15 × 11 × 0.8 cm, connected to a plane electric heater. The heater is sandwiched between the aluminum plate and a 10-mm-thick Teflon plate. Due to the low thermal conductivity of Teflon, the power generated by the heater is mostly directed towards the aluminum plate, termed "heated plate". The heated plate is placed inside a cabinet whose dimensions (24 × 21 × 15 cm) are those typical of an electronic equipment box employed for UAV remote sensing surveys.

The cabinet is thermally insulated by 2 cm-thick polystyrene walls, as shown in fig.2. Since experiments were conducted in a laboratory room, no high-reflectivity external coatings (to prevent solar radiation absorption in outdoor conditions) were considered. The cabinet is equipped with side openings, to permit the forced convection of external air through a fan operating in pressure or suction mode, and with two lateral vanes to accommodate cold gel packs, as displayed in fig.3. The use of cold gel packs is expected to improve the cooling performance, in transient conditions, in combination with air ventilation. The side openings can be sealed, as appears in the photograph of fig.2, in order to investigate the effect provided by a fan placed inside the box, without any air exchange with the laboratory room; in this case, the fan function is to promote an efficient mixing of internal air, cooled by the contact with the cold gel pack surfaces.

The experiments were conducted by delivering 24 W to the heater through a DC power supply. This value of the power dissipated inside the box is of the same order of magnitude of that involved in typical UAV-based, remote sensing applications. Two different scenarios have been considered: (i) the cooling system and the power supplied to the heated plate are activated simultaneously for the entire test duration of 20 minutes, (ii) the power is supplied to the plate for 40 minutes but the box is cooled only during the last 20 minutes of the test. The first scenario is representative of the real operating conditions, with the sensors working throughout the UAV flight, the second scenario is indicative of the response of the cooling system activated with the electronics already switched on, as it can occur, for instance, during manual operations inside the box (replacement of memory cards, sensor substitutions, etc.) with the drone still on the ground.

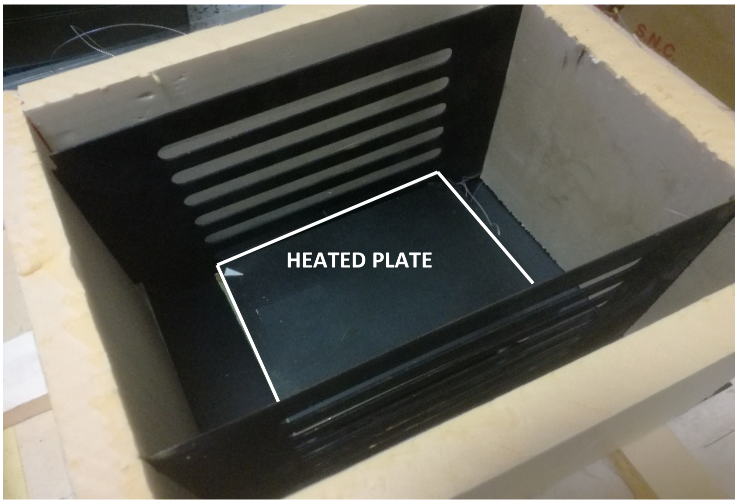

Figure 2. View of the box containing an electrically heated plate.

Several 0.5-mm-dia, type-T, sheathed thermocouples, calibrated to ± 0.1 K, were employed to measure the temperature of the heated plate (plate temperature T_p) and of the air inside the box. The spots where thermocouples were located are schematically shown in fig.3, where TC No.1 is the temperature sensor placed inside the aluminum plate and TC No. 2−7 are those used to measure the air temperature in different spots. The mean air temperature T_{air} inside the box was roughly calculated by averaging the six local air temperature values. The air and plate temperature variations over time were recorded by a data acquisition system. In addition to temperature measurements, local air velocity over a large number of spots inside the box was measured by a hot-wire anemometer (Alnor-TSI Model 275). Temperature and relative humidity of air in the laboratory room were taken in the 27−28 °C and 40−60% ranges, respectively. Further details concerning the experimental setup and the operating conditions are given in [13].

The cooling techniques of the heated plate inside the box are reported in Table 1. They include: (i) the conventional cooling based on external ventilation of air with or without the use of internal gel packs, (ii) the cooling based on internal gel packs with an internal fan, (iii) the passive cooling provided by natural convection, radiation, and the internal gel packs.

A small computer fan (92×92×25 mm, nominal 2500 rpm, maximum flow capacity 43.5 cubic feet per minute) was used for forced convection experiments. The fan was either accommodated inside a side wall of the box, to promote the external air renewal through a vent opening (having a free-flow area of 12 cm^2 and located on the opposite box side wall, as shown in fig.3), or placed inside the box, close to one of the box corners, to promote the internal air ventilation without any air renewal. Either two reusable cold gel packs (frontal dimensions: 22×10 cm, weight: 0.31 kg. freezing temperature about −13°C) or two instant cold packs (frontal dimensions: 18 ×14 cm, weight: 0.28 kg), were used in combination with external or internal air ventilation. Before their use, the cold gel packs were stored at either −18 or +8°C, in order to perform experiments at different starting temperatures, the latent heat of the refrigerant being exploited only in the first case. Conversely, the instant cold packs, whose working principle is based on an endothermic reaction, did not require to be kept in a refrigerator.

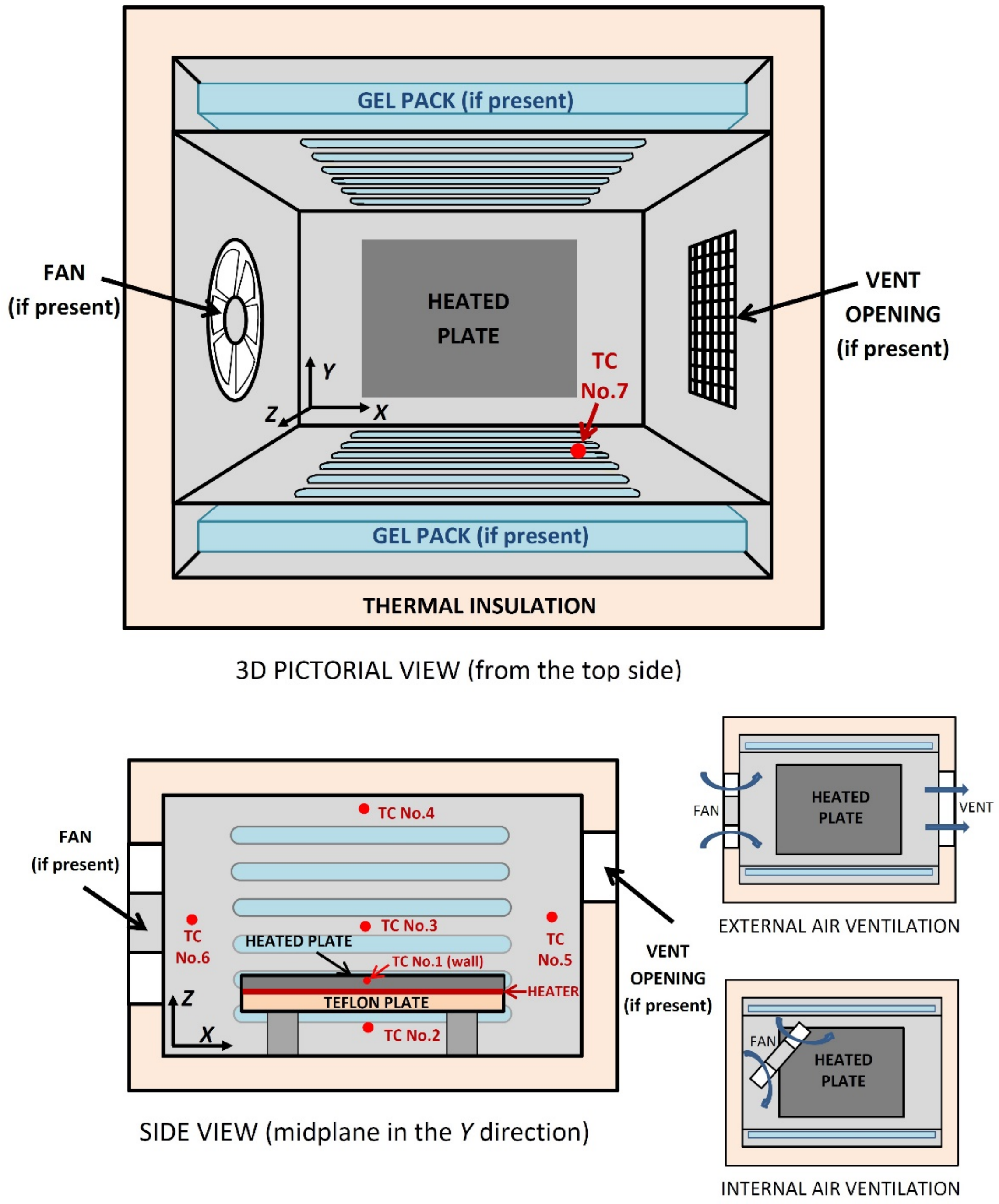

Figure 3. Pictorial, side, and top views of the electronic equipment box used in the experiments.

Table 1. Cooling techniques tested in the experiments.

Configuration	*External air ventilation*	*Internal air ventilation*	*Gel packs (initial temperature)*
A	No	No	No
B	Yes (pressure mode)	No	No
C	Yes (suction mode)	No	No
D	Yes (pressure mode)	No	−18°C
E	Yes (suction mode)	No	−18°C
F	No	Yes	−18°C
G	No	Yes	+8°C
H	No	Yes	Instant cold packs
I	No	No	−18°C
J	No	No	+8°C

3. Results and discussion

Experimental results obtained for the first scenario (power supplied to the heater and cooling of the box from the same time instant) are presented in figs. 4−6.

Plate and air temperature time-evolutions in the case of the forced convection of external air are displayed in fig.4. Tests were conducted with the fan operating either in pressure (Configs. B and D) or suction (Configs. C and E) mode, and without (Configs. B and C) or with (Configs. D and E) internal cold gel packs. The mean velocities measured inside the box (evaluated as the average of the maximum local values recorded at each spot varying the orientation of the hot wire) were 0.8 m/s in the pressure mode and 1.1 m/s in the suction mode. The plate temperature distribution over time for the no-cooling condition (Config. A) is plotted for the purpose of comparison. First, attention is focused onto the forced convection of external air without cold gel packs, which represents the standard cooling mode of electronics in several applications. As compared with the no-cooling condition (Config. A), the external air ventilation leads to reductions in the heated plate temperature by up to 13 K; it is worth noting that the pressure mode of the fan (Config. B) provides slightly better cooling conditions than the suction mode (Config. C). Second, the combined effect of external air ventilation and cold gel packs (at the starting temperature of −18°C) is considered. The presence of the cold gel packs permits a further reduction of heated plate temperatures, but the extent of this reduction due to gel packs is limited (up to 3−4 K), with the pressure mode (Config. D) yielding again a slightly better cooling performance as compared with the suction mode (Config. E).

Figure 5 shows the results obtained when the cold packs are used in the presence of internal air circulation, provided by the same fan employed for the external air, forced convection, experiments. According to this alternative cooling solution, the internal air is cooled by the cold pack surfaces (which are expected to absorb a large part of the heat dissipated by the plate) and efficiently mixed by the fan action. Experiments were conducted with either reusable gel packs at two different initial temperatures (−18°C, Config. F or +8°C, Config. G) or instant cold packs (Config. H). The internal air velocity (again evaluated as the average of the maximum local values recorded at each spot varying the orientation of the hot wire) was about 1.6 m/s. Inspection of fig. 5 reveals that the internal ventilation with cold gel packs represents a very effective cooling solution, with peak plate temperatures reduced by 20 K for Config. G and 28 K for Config.F. Instant cold packs (Config. H), representing a cheap and more practical solution in real applications (UAV-based remote sensing), are characterised by a cooling performance similar to that achieved with cold gel packs at +8°C (Config. G). Figure 5 also displays results obtained with cold gel packs at initial temperatures of either −18°C (Config. I) or +8°C (Config. J) without any forced circulation of air. Experiments showed that the air temperature inside the box is relatively low and comparable to that occurring for internal ventilation and same cold gel pack starting temperature. However, due to the weak natural currents induced inside the box, the cooling mode based on the cold packs without fan-induced air circulation is not particularly efficient, with maximum reductions of the plate temperature of only 7 K.

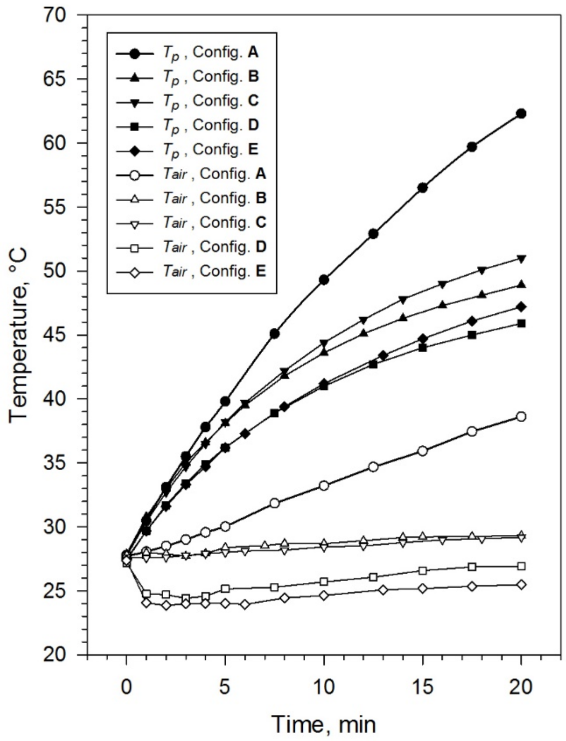

Figure 4. Heated plate temperature T_p and indoor air temperature T_{air} versus time. Cooling by external air ventilation without and with cold gel packs, first scenario.

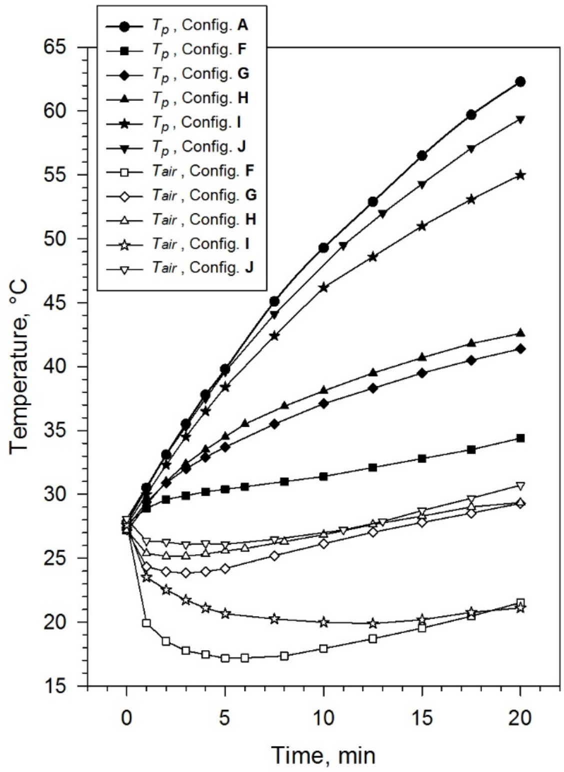

Figure 5. Heated plate temperature T_p and indoor air temperature T_{air} versus time. Cooling by internal air ventilation with cold gel packs and by cold gel packs only, first scenario.

Figure 6 provides a synthetic comparison of heated plate temperatures recorded for some of the cooling solutions considered in the experiments: the external air ventilation alone (Config. B) or combined with gel packs at −18°C (Config. D), the internal air ventilation combined with gel packs at either −18°C (Config. F) or +8°C (Config. G), and the presence of gel packs at −18°C without ventilation (Config. I). Configuration F (internal ventilation + gel packs at −18°C) clearly emerges as the most effective cooling mode. Even in the presence of a higher initial temperature of the cold gel packs (+8°C, Config. G), the heated plate temperatures provided by the internal air ventilation are lower than those given by the external air ventilation with or without cold packs (Configs. D and B, respectively). The comparison between results for Configs. F and I shows that the cold gel packs alone without an effective air movement are unable to guarantee an efficient cooling of the heated plate.

The same comparative analysis (fig.7) has been conducted for the second scenario, where the component is continuously heated for 40 min but the cooling is activated only after 20 min. Obviously, heated plate temperatures have a common behaviour during the first half of the transient, before the cooling starting. As the box is cooled, measured plate temperature distributions are consistent with the previously discussed results for the first scenario. Again, cold gel packs without any forced air current

(Config. I) are useless, while the external or internal air ventilations provide significant reductions of plate temperatures from their maximum levels. For internal air ventilation with gel packs (Configs. F and G), the temperature of the heated plate is promptly driven toward safe values, while the performance of the external air ventilation cooling (Configs. B and D) is worse.

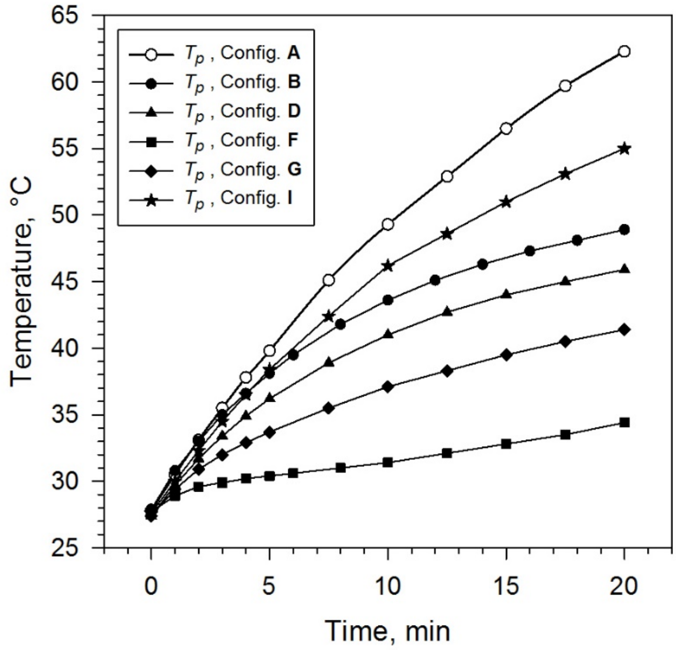

Figure 6. Heated plate temperature T_p versus time. Comparison of different cooling solutions, first scenario.

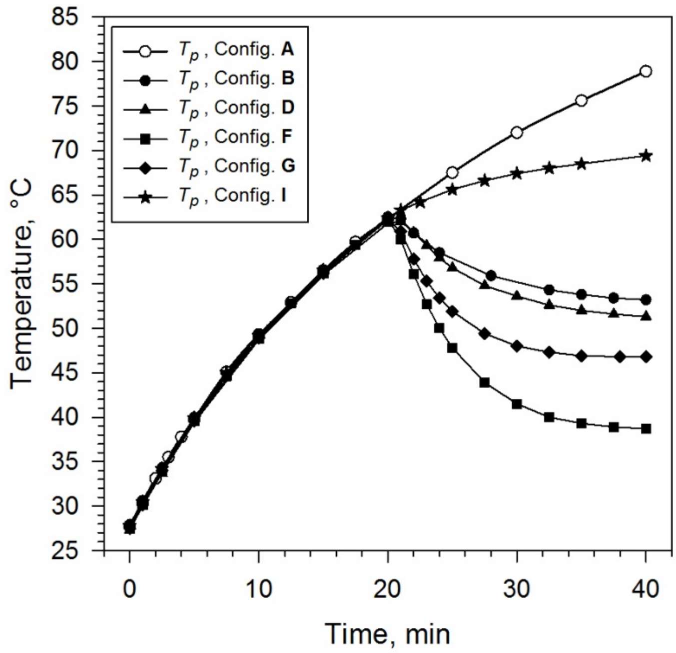

Figure 7. Heated plate temperature T_p versus time. Comparison of different cooling solutions, second scenario.

4. Conclusions

In this study, an experimental investigation of electronic equipment cooling inside a box in transient conditions has been carried out. Dimensions and thermal load of the box are similar to those occurring in UAV-based remote sensing applications when sensors are housed inside a cabinet mounted underneath the drone. The main outcomes are here summarized.

The use of cold gel packs combined with the internal air ventilation of the box containing the electronic instrumentation represents an effective, practical, and cheap cooling solution of electronics when desired temperature levels have to be maintained below given thresholds for a limited amount of time. The majority of heat released by the electronic devices is absorbed by the cold gel packs, while the fan induces efficient mixing of the internal air and relatively high heat transfer coefficients between the plate and the convective fluid. It was found that cold gel packs and internal air ventilation perform better than the external air ventilation even when the initial temperature of the gel pack is largely higher than its freezing temperature (and thus when only its single-phase heat storage capacity is exploited). Conversely, cold gel packs coupled with external air ventilation provide only a marginal contribution to the cooling of the electronic component. Moreover, the cooling of electronics by internal air circulation, with all the box sides sealed, has a further advantage over the external air ventilation since it excludes the occurrence of undesired intrusion inside the box of rain and dust through the vent openings, which could compromise the sensor functionality in outdoor conditions.

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