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An economical dual hot-wire liquid water flux probe design

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ABSTRACT

The velocity, liquid water content (LWC) and their product, the liquid water flux (LWF), are of interest for research in environmental sciences, fog collection, and free-space communications. This paper provides a design for an economical dual hot-wire LWF probe, which enables the ground-based measurement of velocity, LWC and LWF. The design accounts for the droplet deposition efficiency, prong conduction, saturation and sensitivity. The operating mode and probe configurations are described. Two 125 μm diameter, 5 cm long platinum wires having 2 and 50 °C wire to air temperature offsets would yield measurement uncertainties of about 6% for velocity and from 8 to 22% for the LWC and from 2 to 17% for the LWF given velocities in the range 2 to 8 m/s and LWC in the range 0.2 to 0.8 g/m^3. The lower uncertainties correspond to higher LWF, which is of particular interest in fog collection projects. The recurring costs of the instrument's mechanical and electrical components would be about US $150 per unit. Therefore, the design presented herein is a viable option for large-scale sensor networks.

1. Introduction

The liquid water content (LWC) is of interest for research in environmental sciences, fog collection, and free-space communications. The LWC is correlated with the inorganic and organic content of fog, clouds and dew (Aleksic and Dukett, 2010; Collett et al., 2008; Herckes et al., 2013; Möller et al., 1996; Straub et al., 2012). It has also been used as a detector for fog or cloud events (Berton, 2008; Carrillo et al., 2008).

Measurement of the product of the velocity and the LWC, the liquid water flux (LWF) upstream of fog collectors is necessary to determine the collection efficiency. During 2-week studies in 1987 and 1988, Schemenauer and Joe (1989) found that the large fog collector (LFC) collection efficiency is about 20%. Through an aerodynamic analysis, Rivera (2011) concluded that the maximum collection efficiency for a typical LFC should be about 30%. Continuous monitoring of LWF is needed to verify his conclusion, to measure the effects of instantaneous conditions on efficiency, and to inform the collector design process. Furthermore, continuous LWF measurements could aid the assessment of the collection efficiency of plants and animals.

Visibility, which is also considered an indicator of a fog event, is related to LWC and the droplet number concentration (Gultepe et al., 2006). Similarly, the signal attenuation in free-space communication is positively correlated with the level of LWC (David et al., 2012; Khan et al., 2012). Therefore, continuous monitoring of LWC could become a useful component of such systems if signal strength could be varied to accommodate environmental conditions.

Baumgardner et al. (2011) described the many techniques for measuring characteristics of LWC using airborne measurements. Methods based in optics and radiations are also commonly used in ground-based observations (for example, see Gultepe et al., 2009). Carrillo et al. (2008) described an economical optical cloud/fog detector, which, with calibration, could also provide measurements of LWC. However, the design presented in this paper was motivated by very low-budget research using large-scale remote wireless sensor networks (Collins et al., 2006). Therefore, these devices were dismissed because of their relatively high cost and power requirements.

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Heated element techniques measure liquid, ice, or total water content as a function of the heat used to evaporate water in contact with one or more heated elements. Large diameter aggregate LWC probes designed for use at aircraft speeds (Strapp et al., 2003) would have low deposition efficiency at ground wind velocities. To increase the deposition efficiency of a standard sensor in ground conditions, the relative velocity can be increased artificially by moving the sensor (e.g., on a rotating arm), a method used in laboratory tests, (e.g., Keith et al., 1986) or by drawing air past the probe (e.g., Droplet Measurement Technologies, Hot-Wire Liquid Water Sensor optional aspirator). However, this would increase the cost, power consumption and complexity of the instruments, making them unsuitable for ground-based measurements in a low-budget autonomous remote sensor network.

Very small diameter droplet distribution measuring probes are suitable for ground-based or balloon- or helicopter-borne instrument platforms. Siebert et al. (2007) showed that a 5 μm diameter wire (Dantec type 55P01) would survive droplet impact in a wind tunnel and deployed on a helicopter in a cloud. The KLD Labs Portable Droplet Counter can even measure the droplet diameter distribution (Dodge, 1987). However, the instruments are too delicate or expensive to be practical in large-scale autonomous ground-based remote sensing system.

This paper describes a new low-cost, low-power dual hot-wire liquid water flux probe suitable for ground-based applications. Two bodies of knowledge are relevant to this project: hot-wire probes and fog characteristics.

1.1. LWC hot-wire probes

The Johnson–Williams Cloud Water Meter and the Commonwealth Scientific and Industrial Research Organisation (CSIRO, or King) liquid water probes have been the most commonly used airborne LWC probes (for a comparison, see Feind et al., 2000). A LWC hot-wire probe is used to collect and evaporate water droplets. The LWC can be calculated using measurements of the relative velocity, ambient temperature, the wire temperature, and the electrical power needed to maintain the wire temperature.

Vidaurre et al. (2011) described various LWC and total (liquid and frozen) water content (TWC) hot-wire probes and gave an account of their performance on aircraft in an icing research study. The rest of this introduction is focused on the principles of the King probe design (King et al., 1978, 1981; Bradley and King, 1979; Biter et al., 1987) upon which our new probe design is based.

The King probe uses a wire sensor maintained at a constant temperature. The electrical power required to maintain the wire temperature is a function of the wire geometry and temperature, and the relative velocity, temperature and the LWC. The wire is generally assumed to be perpendicular to the wind either because of its high velocity or because it is mounted on a wind vane (Korolev et al., 1998).

The power balance for a heated wire perpendicular to advected fog is shown in Eq. (1).

$$P_{elect} = P_{evap} + P_{conv} + P_{cond} + P_{store} \tag{1}$$

where P_{elect} is the electrical power input (Joule heating), P_{evap} is the power needed to heat and evaporate the impacting water droplets, P_{conv} is power transferred to air via convective cooling and P_{cond} is the power lost to the prongs through conduction. The rate of heat storage, P_{store}, is neglected because the time response of the wire is very short (on the order of 1 second).

In practice, P_{elect} is determined from measurements of the current through and voltage across the sensing wire. The calculation of P_{conv} is based on the Nusselt number, Nu, thermal conductivity of air, k_a, wire length and wire to air temperature difference. However, a "dry calibration" was recommended by King et al. (1978) to reduce the uncertainty in this term. This calibration would also account for P_{cond}.

The evaporative term, shown in Eq. (2), can be written in terms of the sensor length (L_s), diameter (D_s), and temperature (T_s), air temperature (T_a), heat capacity (c), latent heat of evaporation (L) and LWF, which is the product of the velocity (v) and the LWC (w).

$$P_{evap} = L_s D_s v w [L + c(T_s - T_a)] \tag{2}$$

The LWC can be obtained by combining Eqs. (1) and (2) and solving for the LWC as shown in Eq. (3).

$$w = \frac{P_{elect} - P_{conv} - P_{cond} - P_{store}}{L_s D_s\, v[L + c(T_s - T_a)]} \tag{3}$$

Therefore, given measurements of the sensor geometry, wire and air temperatures, and the relative velocity and a dry calibration, the LWC can be estimated. The sensor wire temperature is established by balancing a Wheatstone bridge circuit containing the sensor wire (see Section 3).

1.2. Fog characteristics

The LWC, size distribution of water droplets, velocity, and temperature all factor into the design. Representative ranges from the Atacama Desert of Chile were used for this design. Schemenauer and Joe (1989) showed that, for the specific case of the "camanchaca" (typical advection fog of the north of Chile), 99% of the LWC is in droplets within the size range between 4 and 22 μm and the LWC is in the range 0.2 to 0.7 g/m^3. Westbeld et al. (2009) also studied the droplet diameters of camanchaca and found that droplet diameters between 5 and 38 μm represent more than 99% of the LWC with an average LWC of 0.35 g/m^3.

Schemenauer and Joe (1989) reported a range of velocities from 2 to 7 m/s with an average wind velocity of about 5 m/s. The data from a weather station at *Desierto de Atacama, Caldera Ap.* (27°15′S 70°46′W) for 2011 from the *Dirección General de Aeronáutica Civil, Dirección Meteorológica de Chile, Climatología*[1] show the maximum velocity in a given day is typically about 6 m/s and the temperature ranges from about 3 to 30 °C.

Consequently, the LWC range 0.2 to 0.8 g/m^3, velocity range 2 to 8 m/s, and temperature range 1 to 30 °C were used for the design and analysis.

[1] http://164.77.222.61/climatologia/, accessed January 2013.