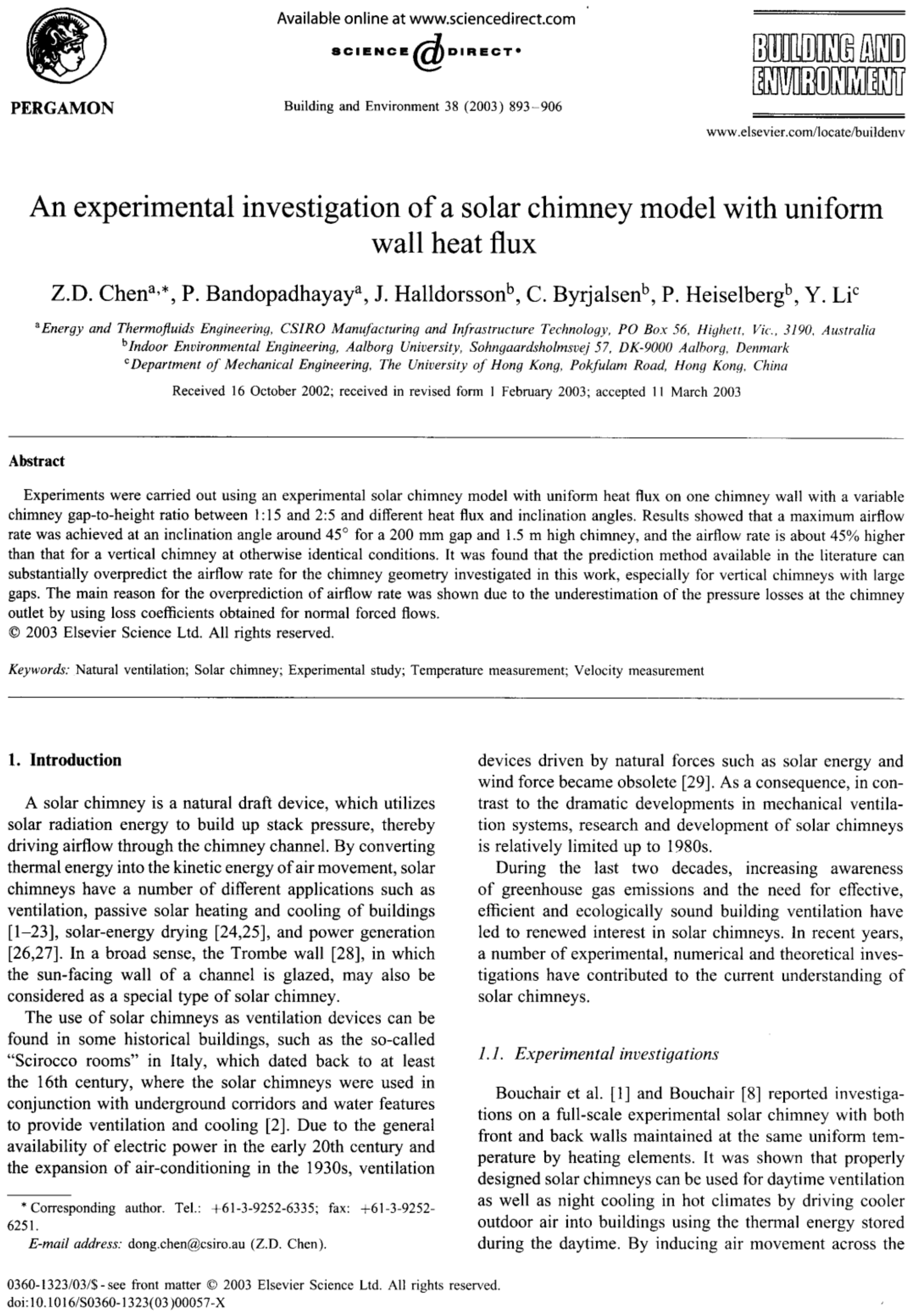
Anexos

A. Modelo para calcular el flujo de aire volumétrico en el colector



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An experimental investigation of a solar chimney model with uniform wall heat flux

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Abstract

Experiments were carried out using an experimental solar chimney model with uniform heat flux on one chimney wall with a variable chimney gap-to-height ratio between 1:15 and 2:5 and different heat flux and inclination angles. Results showed that a maximum airflow rate was achieved at an inclination angle around 45° for a 200 mm gap and 1.5 m high chimney, and the airflow rate is about 45% higher than that for a vertical chimney at otherwise identical conditions. It was found that the prediction method available in the literature can substantially overpredict the airflow rate for the chimney geometry investigated in this work, especially for vertical chimneys with large gaps. The main reason for the overprediction of airflow rate was shown due to the underestimation of the pressure losses at the chimney outlet by using loss coefficients obtained for normal forced flows.

Keywords: Natural ventilation; Solar chimney; Experimental study; Temperature measurement; Velocity measurement

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1. Introduction

A solar chimney is a natural draft device, which utilizes solar radiation energy to build up stack pressure, thereby driving airflow through the chimney channel. By converting thermal energy into the kinetic energy of air movement, solar chimneys have a number of different applications such as ventilation, passive solar heating and cooling of buildings [1–23], solar-energy drying [24,25], and power generation [26,27]. In a broad sense, the Trombe wall [28], in which the sun-facing wall of a channel is glazed, may also be considered as a special type of solar chimney.

The use of solar chimneys as ventilation devices can be found in some historical buildings, such as the so-called "Scirocco rooms" in Italy, which dated back to at least the 16th century, where the solar chimneys were used in conjunction with underground corridors and water features to provide ventilation and cooling [2]. Due to the general availability of electric power in the early 20th century and the expansion of air-conditioning in the 1930s, ventilation devices driven by natural forces such as solar energy and wind force became obsolete [29]. As a consequence, in contrast to the dramatic developments in mechanical ventilation systems, research and development of solar chimneys is relatively limited up to 1980s.

During the last two decades, increasing awareness of greenhouse gas emissions and the need for effective, efficient and ecologically sound building ventilation have led to renewed interest in solar chimneys. In recent years, a number of experimental, numerical and theoretical investigations have contributed to the current understanding of solar chimneys.

1.1. Experimental investigations

Bouchair et al. [1] and Bouchair [8] reported investigations on a full-scale experimental solar chimney with both front and back walls maintained at the same uniform temperature by heating elements. It was shown that properly designed solar chimneys can be used for daytime ventilation as well as night cooling in hot climates by driving cooler outdoor air into buildings using the thermal energy stored during the daytime. By inducing air movement across the

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Nomenclature

A	channel cross-sectional area (m^2)
A_{in}	chimney inlet area (m^2)
A_{out}	chimney outlet area (m^2)
B	buoyancy flux (m^4/s^{-3})
c_{in}	inlet pressure loss coefficient
c_{out}	outlet pressure loss coefficient
C_p	air specific heat capacity at ambient temperature (J/kg ·° C)
D_h	hydraulic diameter of the chimney channel (m)
f	friction factor for the channel wall
g	gravitational acceleration rate (m/s^2)
Gr^*	modified Grashof number
H	chimney height (m)
h	height along the chimney (m)
Pr	Prandtl number of air
Q	airflow rate in the chimney (m^3/s)
q	heat flux (W/m^2)
T	local temperature (°C)
T_{amb}	ambient temperature (°C)
T_{ave}	average air temperature (°C)
$T_{average}$	average air temperature inside the chimney (°C)
T_w	wall surface temperature (°C)
u	local airspeed (m/s)
u_1	characteristic air velocity
w	chimney width (m)
y	distance from the heated wall (m)

Greek symbols

α	chimney inclination angle
β	air expansion coefficient (1/°C)
δ	momentum boundary layer thickness (m)
δ_t	thermal boundary layer thickness (m)
ΔP_L	total pressure loss (Pa)
ΔP_S	stack pressure (Pa)
ν	air kinetic viscosity (m^2/s)
ρ	air density at ambient temperature (kg/m^3)

room or by evaporative cooling of the incoming air, thermal comfort in buildings may be achieved using solar chimneys in buildings.

It was also shown by Bouchair et al. [1] and Bouchair [8] that there is an optimum chimney width (about one-tenth of the chimney height) at which a maximum ventilation flow rate can be achieved. Further increase in the chimney gap results in a decrease in the airflow rate due to the occurrence of back flow at the outlet of the chimney. Numerical modeling by Gan and Riffat [13] confirmed the existence of the optimum chimney gap-to-height ratio. Recently, small-scale modeling by Spencer et al. [30] and numerical simulations by Chen and Li [31] for solar chimneys with uniform wall heat flux also demonstrated the existence of an optimum chimney gap-to-height ratio. It is also shown that the optimum gap-to-height ratio is dependent on the chimney inlet design. A large inlet size can result in a large optimum gap-to-height ratio due to the delay of the occurrence of reverse flow.

Different designs of roof solar collectors were studied by Khedari et al. [10]. The roof solar collectors acted as solar chimneys to induce natural ventilation into houses. It was shown that to achieve the maximum ventilation flow rate, the optimum dimension of the collector is 1 m long, tilted at 30° and with a collector gap of 140 mm. Khedari et al. [19] and Hirunlabh et al. [23] implemented different roof solar collector designs and found that when using roof solar collectors alone, there is little potential to induce sufficient airspeed to satisfy occupant comfort in hot climates. In order to increase airspeed in a test room, two roof solar collectors together with three different types of solar chimneys were installed and tested by Khedari et al. [20] in the same building. Although the resulting air change rate per hour in the test room was high (8–15), the air movement induced by these solar chimneys was still too low (average 0.04 m/s) for thermal comfort of occupants with an indoor temperature of about 35–37°C. This conclusion appears to be in agreement with the observations of Barozzi et al. [3] who investigated a solar-chimney-based ventilation system for buildings using a 1:12 small-scale model in which the roof performs as a solar chimney.

Moshfegh and Sandberg [15] investigated buoyancy-driven air movement behind photovoltaic panels in order to cool down the photovoltaic cells. The system has the same principle as a solar chimney with uniform heat on the sun-facing wall, while the other walls remain unheated. Experimental results revealed that for input heat flux equal to or greater than 200 W/m^2, dependent on the surrounding wall emissivity, up to 30% of the heat input may be transferred to the otherwise unheated wall via radiation. It was also found that an increase in the surrounding surface emissivity increases the airflow rate due to the increased proportion of heat transferred to the unheated wall. By varying the inclination angle of the chimney channel, Sandberg and Moshfegh [16] showed that inclination of the chimney decreases ventilation flow rate with the same heat flux.

Kumar et al. [14] studied indoor air quality in a prototype house with a solar chimney system, and showed that passive outdoor air ventilation is effective in reducing indoor air contaminants. By comparing the performance of a conventional brick solar chimney and a solar chimney with the sun-facing wall replaced by glazing, Afonso and Oliveira

[21] showed that the glazed solar chimney drew about 10–20% more air through the chimney.

1.2. Numerical modeling

Barozzi et al. [3] used a two-dimensional computational fluid dynamics (CFD) method in the investigation of the air movement inside their 1:12 building model. Although the CFD model used was considered to be primitive (it did not account for turbulence and three-dimensional effects), reasonable agreement was reported between experimental temperature and velocity measurements and numerical predictions.

A three-dimensional CFD program with a standard k–ε turbulence model was used by Awbi and Gan [4] for modeling air movement in solar chimneys. Good agreement was achieved for the airflow rate between numerical predictions and the experimental results obtained by Bouchair [8]. A similar approach has been used by Gan [12] and Gan and Riffat [13] for numerical simulation of air movement in solar chimneys.

Moshfegh and Sandberg [15] investigated air movement behind photovoltaic panels. Their two-dimensional numerical model adopted a standard k–ε turbulence model and wall function. In addition, radiation effects were also considered in their numerical model. Predicted air velocity and temperature distributions were shown to be in good agreement with their experimental results. Rodrigues et al. [18] investigated a two-dimensional solar chimney numerically with a standard k–ε turbulence model and wall function. Details of the velocity and temperature field inside the solar chimney were reported.

In these previous numerical investigations, simulations were carried out with a computational domain defined by the two solar chimney walls and the chimney inlet (or the room inlet) and outlet in order to minimize the computation efforts. In reality, contraction and expansion and thus pressure losses occur at the chimney inlet and outlet, respectively. In order to account for chimney inlet pressure loss, Awbi and Gan [4] applied an effective discharge coefficient at the chimney inlet. The effect of this departure from reality on the overall airflow rate prediction is still not clear and further investigation is needed.

1.3. Analytical investigations

For solar chimneys with uniform wall temperature, Awbi and Gan [4] and Awbi [9] obtained air temperature distribution along the chimney channel by considering the heat transfer coefficient along the heated surface and assuming uniform temperature distributions across the same vertical height. By balancing the stack pressure and the total pressure loss along the airflow path, the airflow rate induced by a solar chimney with uniform wall temperature was obtained. Good agreement was reported between the predicted flow rate and the experimental results reported by Bouchair [8]. Bansal et al. [5,7], AboulNaga [11], and AboulNaga and Abdrabboth [22] used an essentially similar approach for flow rate predictions induced by a solar chimney with uniform wall temperature.

Considering heat balance, Sandberg [17] obtained an expression for the airflow rate through a rectangular channel with uniform wall heat flux. It was shown that the predicted airflow rate was in good agreement with the experimental results for a rectangular channel with one wall heated at uniform heat flux and a channel gap-to-height ratio of 1:28. A similar approach was also used by Fath [6] for the design of a natural draft solar fan with uniform wall heat flux.

It is noted that the above flow rate prediction methods are based on the assumption of uniform temperature distributions across the same vertical height. As proved by Awbi [9] and Sandberg [17], these prediction methods are applicable to chimneys with a small gap-to-height ratio of less than or close to 1:10. For wide chimneys, the assumption of uniform temperature distribution may no longer be valid. Furthermore, the occurrence of reverse flows near the chimney outlets for wide chimneys may also make these theoretical predictions inadequate. Another embedded assumption of these prediction methods is that the pressure loss coefficients at the chimney inlet, outlet and along the chimney channel can be evaluated with the corresponding data for forced flows. To date, no study has been undertaken to verify this assumption. Consequently, further investigations are necessary to clarify the conditions under which these prediction methods can be confidently applied.

In this work, experiments were carried out using a simple solar chimney experimental model with a uniform heat flux on one chimney wall. Air temperature and airflow rates for different chimney gaps, heat fluxes and different chimney inclination angles were measured to provide further understanding of the ventilation performance of solar chimneys. Experimental results are compared with the predictions based on heat balance analysis, and discrepancies between the theoretical assumptions and the experimental results are discussed.

2. Analysis

It is one of the major tasks for solar chimney designers to predict the airflow rates under given solar radiation intensity. In order to facilitate the interpretation of the experimental results obtained in this work, an analysis is included here for a solar chimney with a uniform wall heat flux.

As discussed above, all prediction methods available in the literature are based on the assumption of uniform air temperature across chimney gaps [4–7,9,11,17]. Assuming uniform air temperature at the same height inside the chimney, energy balance yields

$$qhw = Q\rho C_p(T_{\text{average}} - T_{\text{amb}}), \quad (1)$$

where h is the height along the chimney, w is the chimney width, q is the heat flux, Q is the airflow rate in the chimney, ρ and C_p are air density and specific heat capacity at ambient temperature, respectively, T_{average} is the average air temperature inside the chimney at the height of h, and T_{amb} is the ambient temperature.

Then, the stack pressure, ΔP_S, can be obtained by the following integration:

$$\Delta P_S = \int_0^H \frac{(T_{\text{average}} - T_{\text{amb}})\rho g \cos\alpha}{T_{\text{amb}}}\,dh = \int_0^H \frac{qhwg\cos\alpha}{QC_pT_{\text{amb}}}\,dh = \frac{qwgH^2\cos\alpha}{2QC_pT_{\text{amb}}} = \frac{\rho BH\cos\alpha}{2Q}, \tag{2}$$

where α is the chimney inclination angle from vertical, H is the chimney height, and B is the buoyancy flux:

$$B = \frac{gqwH}{\rho C_p T_{\text{amb}}}.$$

The pressure loss along the air path, ΔP_L, may be expressed as

$$\Delta P_L = c_{\text{in}}\frac{\rho(Q/A_{\text{in}})^2}{2} + c_{\text{out}}\frac{\rho(Q/A_{\text{out}})^2}{2} + f\frac{H}{D_h}\frac{\rho(Q/A)^2}{2}, \tag{3}$$

where A is the channel cross-sectional area, A_{in} and A_{out} are the inlet and outlet areas, f is the friction factor for the channel wall, c_{in} and c_{out} are the inlet and outlet pressure loss coefficients, and D_h is the hydraulic diameter of the chimney channel.

By balancing the stack pressure (Eq. (2)) and the pressure losses along the air path (Eq. (3)), the ventilation flow rate, Q, for a chimney with a uniform wall heat flux can be obtained as follows:

$$Q = A\left(\frac{B\cos\alpha}{2\psi}\right)^{1/3}, \tag{4}$$

where

$$\psi = \frac{A}{H}\left[f\frac{H}{2D_h} + \frac{1}{2}\left[c_{\text{in}}\left(\frac{A}{A_{\text{in}}}\right)^2 + c_{\text{out}}\left(\frac{A}{A_{\text{out}}}\right)^2\right]\right]. \tag{5}$$

For the pressure loss coefficients, a general approach is to resort to the available data for normal forced flows. For the case of a rectangular channel with both ends open and heated on a single wall, Sandberg [17] used $c_{\text{in}} = 1.5$, $c_{\text{out}} = 1.0$ and $f = 0.056$, respectively. Eq. (4) has been validated by Sandberg [17] using a rectangular channel with one wall heated at a uniform heat flux and a chimney gap-to-height ratio of 1:28.

From the above analysis, it is seen that the airflow rate is mainly determined by two aspects: (a) the stack pressure built up in the chimney and (b) the pressure losses at the inlet, outlet and along the chimney channel. Consequently, correct evaluations of the average air temperature and the pressure loss coefficients are essential for an accurate prediction of the airflow rate induced by solar chimneys.

3. Experiment

Fig. 1 shows the schematic view of the experimental system. The experimental solar chimney has internal dimensions of 1.5 m high, 0.62 m wide and a variable chimney gap from 100 to 600 mm. The chimney was heated with a uniform heat flux on one wall only. The experiments were carried out inside a 5 m wide ×7 m long ×3.9 m high experimental bay which is part of a large air-conditioned space. Two sides of the bay were the solid brick walls of the large space and the experimental bay was separated from the remaining by heavy curtains to avoid the influence of any air movement caused by ventilation openings outside the bay. There were no ventilation openings arranged inside the experimental bay. The inlet of the chimney was 1 m above the floor.

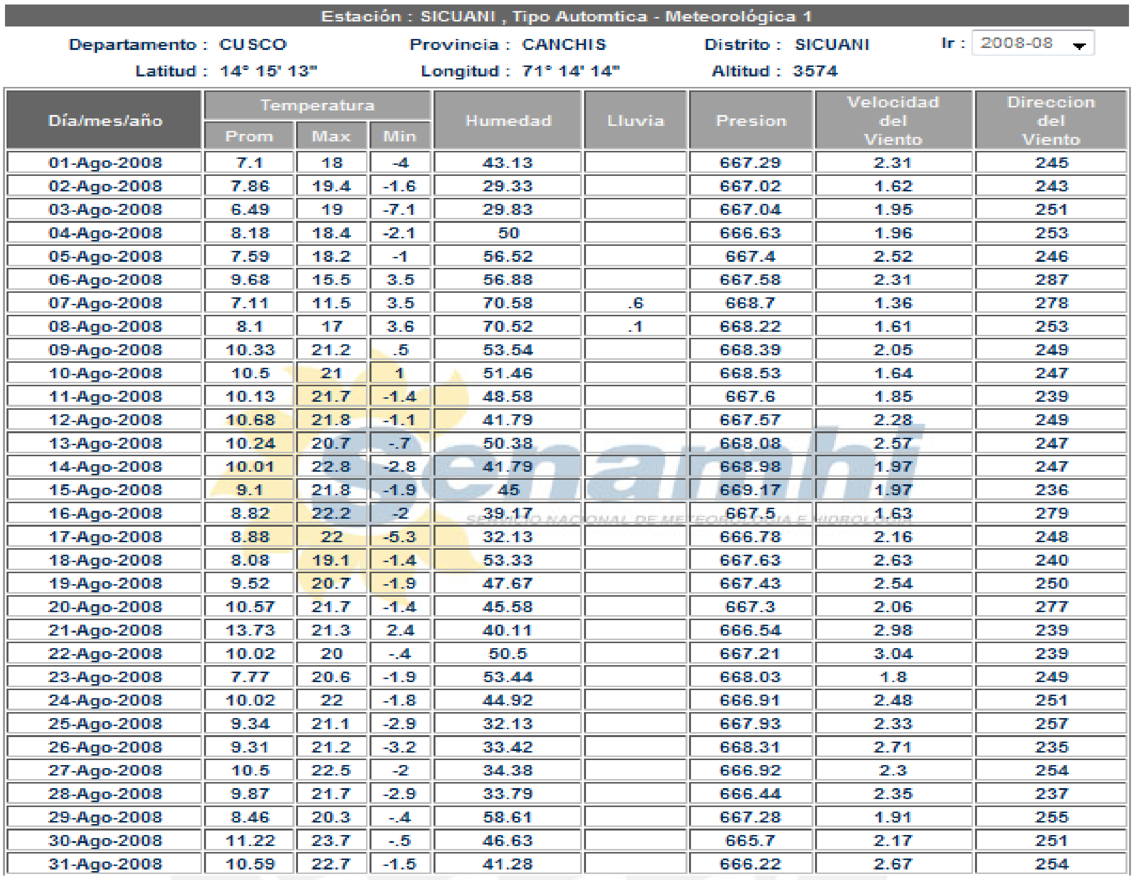
As shown in Figs. 2 and 3, the heated surface of the solar chimney was composed of two 0.12 mm thick, 305 mm wide and 1.46 m long stainless-steel shims connected in series at the bottom of the two shims by a $20 \times 20 \times 615\ \text{mm}^3$ copper bar. A Hewlett Packard 6671A System DC power supplier was used to apply a constant low voltage (< 8 V) on the shims to simulate uniform solar radiation on the heated wall. In order to avoid direct contact, a 5 mm gap was left between the two shims. The heated surface was insulated with 100 mm fiberglass to reduce the heat loss through the heated wall to the ambient air.

The two side walls of the chimney were made of 1500 mm high, 850 mm wide and 6 mm thick plexiglas. The surface opposite the heated shims (the front wall) was 1500 mm high, 620 mm wide and 3 mm thick plexiglas. This front wall facing the heated surface is movable to achieve different chimney gaps. The two side walls as well as the front wall were insulated with 50 mm expanded polystyrene to reduce heat losses. As shown in Fig. 2, the chimney channel can be tilted anticlockwise, which is similar to a solar chimney with the sun-facing wall replaced by glazing.

As shown in Fig. 3, 13 T-type thermocouples were directly soldered onto the back of the stainless-steel shims to measure the local temperatures of the heated surface. The air temperature inside the chimney channel was measured by 7 T-type thermocouples arranged on a stretched bicycle brake wire which can be placed at any position inside the chimney. Temperatures of the insulation materials behind the heated shims and the unheated front wall were also measured to estimate the heat losses through the chimney walls, as well as the radiation heat transferred from the heated shims to the unheated front wall.

Thermocouples were calibrated to within ±0.2°C at 0°C, 40°C and 80°C before being soldered onto the shims, while all the other thermocouples were calibrated

B. Datos meterológicos de Sicuani

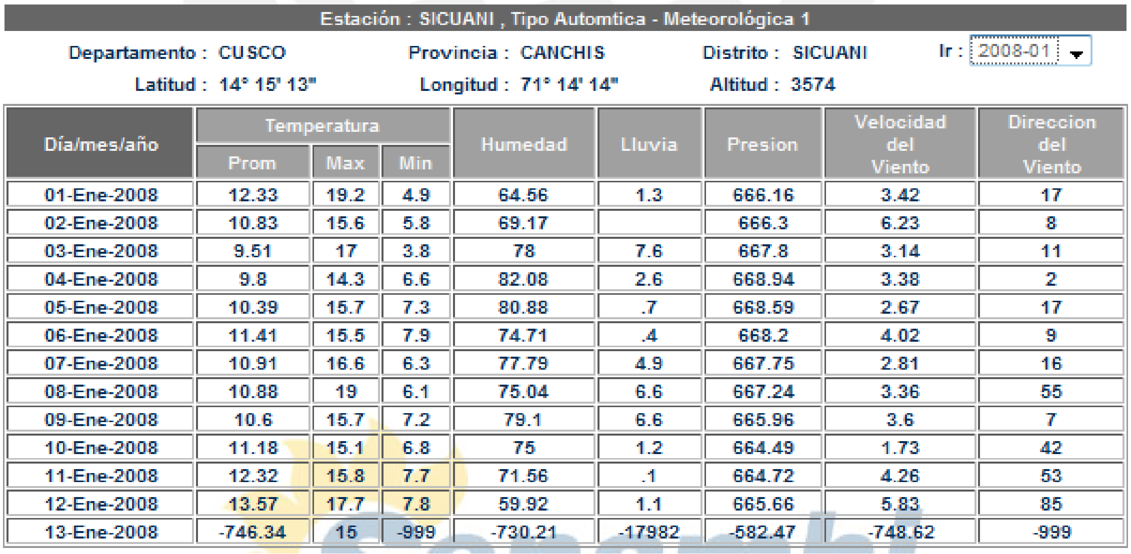


Estación : SICUANI , Tipo Automtica - Meteorológica 1

Departamento : CUSCO Provincia : CANCHIS Distrito : SICUANI Ir : 2008-08

Latitud : 14° 15' 13" Longitud : 71° 14' 14" Altitud : 3574

Día/mes/año	Temperatura			Humedad	Lluvia	Presion	Velocidad del Viento	Direccion del Viento
	Prom	Max	Min					
01-Ago-2008	7.1	18	-4	43.13		667.29	2.31	245
02-Ago-2008	7.86	19.4	-1.6	29.33		667.02	1.62	243
03-Ago-2008	6.49	19	-7.1	29.83		667.04	1.95	251
04-Ago-2008	8.18	18.4	-2.1	50		666.63	1.96	253
05-Ago-2008	7.59	18.2	-1	56.52		667.4	2.52	246
06-Ago-2008	9.68	15.5	3.5	56.88		667.58	2.31	287
07-Ago-2008	7.11	11.5	3.5	70.58	.6	668.7	1.36	278
08-Ago-2008	8.1	17	3.6	70.52	.1	668.22	1.61	253
09-Ago-2008	10.33	21.2	.5	53.54		668.39	2.05	249
10-Ago-2008	10.5	21	1	51.46		668.53	1.64	247
11-Ago-2008	10.13	21.7	-1.4	48.58		667.6	1.85	239
12-Ago-2008	10.68	21.8	-1.1	41.79		667.57	2.28	249
13-Ago-2008	10.24	20.7	-.7	50.38		668.08	2.57	247
14-Ago-2008	10.01	22.8	-2.8	41.79		668.98	1.97	247
15-Ago-2008	9.1	21.8	-1.9	45		669.17	1.97	236
16-Ago-2008	8.82	22.2	-2	39.17		667.5	1.63	279
17-Ago-2008	8.88	22	-5.3	32.13		666.78	2.16	248
18-Ago-2008	8.08	19.1	-1.4	53.33		667.63	2.63	240
19-Ago-2008	9.52	20.7	-1.9	47.67		667.43	2.54	250
20-Ago-2008	10.57	21.7	-1.4	45.58		667.3	2.06	277
21-Ago-2008	13.73	21.3	2.4	40.11		666.54	2.98	239
22-Ago-2008	10.02	20	-.4	50.5		667.21	3.04	239
23-Ago-2008	7.77	20.6	-1.9	53.44		668.03	1.8	249
24-Ago-2008	10.02	22	-1.8	44.92		666.91	2.48	251
25-Ago-2008	9.34	21.1	-2.9	32.13		667.93	2.33	257
26-Ago-2008	9.31	21.2	-3.2	33.42		668.31	2.71	235
27-Ago-2008	10.5	22.5	-2	34.38		666.92	2.3	254
28-Ago-2008	9.87	21.7	-2.9	33.79		666.44	2.35	237
29-Ago-2008	8.46	20.3	-.4	58.61		667.28	1.91	255
30-Ago-2008	11.22	23.7	-.5	46.63		665.7	2.17	251
31-Ago-2008	10.59	22.7	-1.5	41.28		666.22	2.67	254

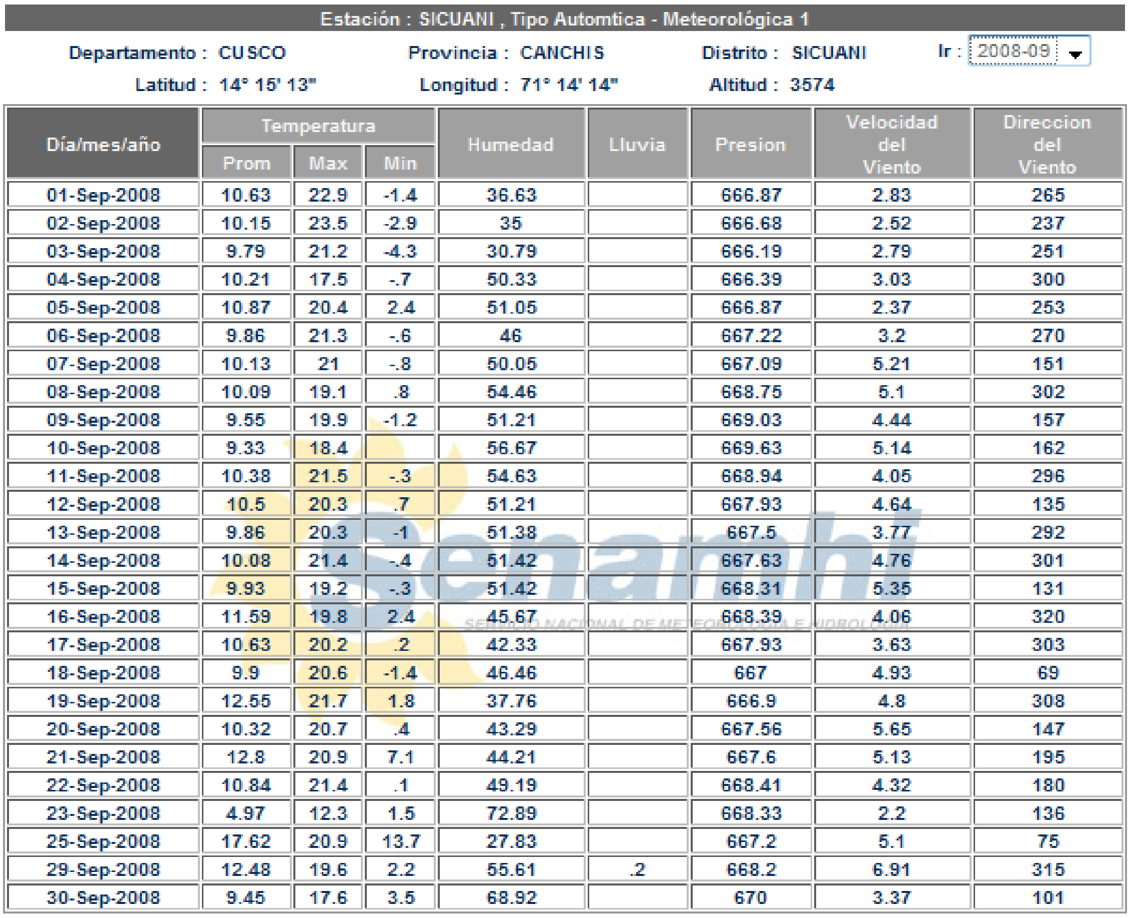


Estación : SICUANI , Tipo Automtica - Meteorológica 1

Departamento : CUSCO Provincia : CANCHIS Distrito : SICUANI Ir : 2008-01

Latitud : 14° 15' 13" Longitud : 71° 14' 14" Altitud : 3574

Día/mes/año	Temperatura			Humedad	Lluvia	Presion	Velocidad del Viento	Direccion del Viento
	Prom	Max	Min					
01-Ene-2008	12.33	19.2	4.9	64.56	1.3	666.16	3.42	17
02-Ene-2008	10.83	15.6	5.8	69.17		666.3	6.23	8
03-Ene-2008	9.51	17	3.8	78	7.6	667.8	3.14	11
04-Ene-2008	9.8	14.3	6.6	82.08	2.6	668.94	3.38	2
05-Ene-2008	10.39	15.7	7.3	80.88	.7	668.59	2.67	17
06-Ene-2008	11.41	15.5	7.9	74.71	.4	668.2	4.02	9
07-Ene-2008	10.91	16.6	6.3	77.79	4.9	667.75	2.81	16
08-Ene-2008	10.88	19	6.1	75.04	6.6	667.24	3.36	55
09-Ene-2008	10.6	15.7	7.2	79.1	6.6	665.96	3.6	7
10-Ene-2008	11.18	15.1	6.8	75	1.2	664.49	1.73	42
11-Ene-2008	12.32	15.8	7.7	71.56	.1	664.72	4.26	53
12-Ene-2008	13.57	17.7	7.8	59.92	1.1	665.66	5.83	85
13-Ene-2008	-746.34	15	-999	-730.21	-17982	-582.47	-748.62	-999



Estación : SICUANI , Tipo Automtica - Meteorológica 1

Departamento : CUSCO Provincia : CANCHIS Distrito : SICUANI Ir : 2008-09

Latitud : 14° 15' 13" Longitud : 71° 14' 14" Altitud : 3574

Día/mes/año	Temperatura			Humedad	Lluvia	Presion	Velocidad del Viento	Direccion del Viento
	Prom	Max	Min					
01-Sep-2008	10.63	22.9	-1.4	36.63		666.87	2.83	265
02-Sep-2008	10.15	23.5	-2.9	35		666.68	2.52	237
03-Sep-2008	9.79	21.2	-4.3	30.79		666.19	2.79	251
04-Sep-2008	10.21	17.5	-.7	50.33		666.39	3.03	300
05-Sep-2008	10.87	20.4	2.4	51.05		666.87	2.37	253
06-Sep-2008	9.86	21.3	-.6	46		667.22	3.2	270
07-Sep-2008	10.13	21	-.8	50.05		667.09	5.21	151
08-Sep-2008	10.09	19.1	.8	54.46		668.75	5.1	302
09-Sep-2008	9.55	19.9	-1.2	51.21		669.03	4.44	157
10-Sep-2008	9.33	18.4		56.67		669.63	5.14	162
11-Sep-2008	10.38	21.5	-.3	54.63		668.94	4.05	296
12-Sep-2008	10.5	20.3	.7	51.21		667.93	4.64	135
13-Sep-2008	9.86	20.3	-1	51.38		667.5	3.77	292
14-Sep-2008	10.08	21.4	-.4	51.42		667.63	4.76	301
15-Sep-2008	9.93	19.2	-.3	51.42		668.31	5.35	131
16-Sep-2008	11.59	19.8	2.4	45.67		668.39	4.06	320
17-Sep-2008	10.63	20.2	.2	42.33		667.93	3.63	303
18-Sep-2008	9.9	20.6	-1.4	46.46		667	4.93	69
19-Sep-2008	12.55	21.7	1.8	37.76		666.9	4.8	308
20-Sep-2008	10.32	20.7	.4	43.29		667.56	5.65	147
21-Sep-2008	12.8	20.9	7.1	44.21		667.6	5.13	195
22-Sep-2008	10.84	21.4	.1	49.19		668.41	4.32	180
23-Sep-2008	4.97	12.3	1.5	72.89		668.33	2.2	136
25-Sep-2008	17.62	20.9	13.7	27.83		667.2	5.1	75
29-Sep-2008	12.48	19.6	2.2	55.61	.2	668.2	6.91	315
30-Sep-2008	9.45	17.6	3.5	68.92		670	3.37	101