

# Study on the Thermal Environment of “Cool Alley” in Chinese Historic Settlements

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**Abstract.** Chinese historic settlements are striking testimonies to the architectural civilization of China. Based on the concept of ‘letting nature take its course’, these settlements promote harmony and unity between architecture and nature, and embody the ecological wisdom of our ancestors. Many of the planning and design strategies utilized in the construction of these settlements are environmentally friendly and resulted in the settlements consuming only a small amount of energy. Consequently, they had the capacity to adapt to changes in the natural environment. This paper focuses on one of these traditional strategies, called ‘cool alley’, an efficient passive-cooling strategy common in the historic settlements of southern China, such as in Fujian province and Guangdong province. With the worsening energy crisis and high requirements of modern living environments, researchers have gradually recognized the importance of ‘cool alleys’ and have begun to assess how their design principles can be applied to modern developments. In this study, the thermal environment of the ‘cool alley’ of a traditional Shoujinliao residence in Quanzhou city, Fujian province was simulated numerically using a three-dimensional unsteady simulation method, rather than a steady simulation method, in order to reveal the dynamic passive-cooling process of the alley. The results of the study can help to promote the modern use of this traditional energy-saving design strategy in architectural design and urban planning.

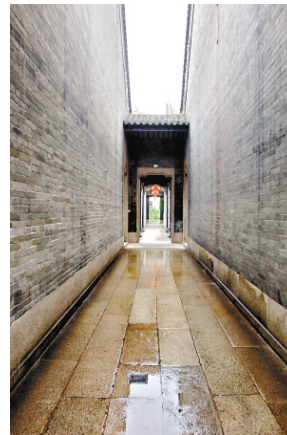
## 1. Introduction

Chinese historic settlements are striking testimonies to the architectural civilization of China. Based on the concept of ‘letting nature take its course’, these settlements promote the harmony and unity between architecture and nature, and embody the ecological wisdom [1] of our ancestors. Many of the planning and design strategies used in the construction of these settlements are environmentally friendly and resulted in the settlements consuming only a small amount of energy. As a result, they had the capacity to adapt to changes in the natural environment. Among these traditional strategies, ‘cool alley’ is widely accepted in academia as an efficient passive-cooling design strategy for very hot and humid summers [2-10].

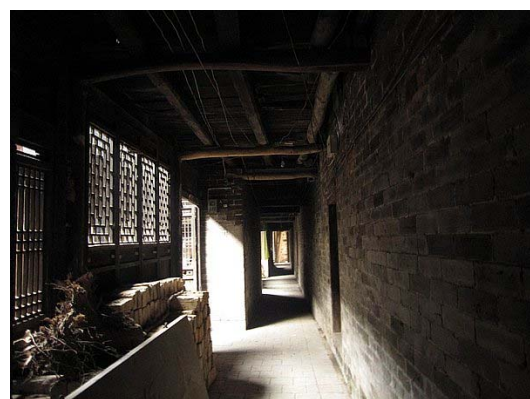
‘Cool alleys’ are classified into two kinds: external cool alleys and internal cool alleys. External cool alleys are narrow alleys between buildings that have widths in the range 0.8–1.5 m and high aspect ratios in the range 3:1–6:1. This kind of alley is common in the historic settlements in areas such as Guangdong province, Fujian province, Anhui province, and Hunan province (see Fig. 1).

Internal cool alleys are long narrow alleys for circulation and ventilation in many historic buildings, especially in areas such as Guangdong province, Fujian province, and Hunan province (see Fig. 2).

Cool alley, as a passive-cooling technique, is achieved mainly by means of spatial layout and architectural design. An analysis of how this technique works would help to promote its application to modern settlements. Thus, these research findings will have essential practical significance for creating sustainable human living environments with low energy consumption. However, most researchers in this area have simply analysed the technical strategies of cool alleys qualitatively [2-6],



**Figure 1.** An external cool alley in a historic settlement in Guangzhou city [Source: gzdaily.dayoo.com]



**Figure 2.** An internal cool alley of a historic village in Hunan province [Source: www.uutuu.com]

while a few others have conducted quantitative studies based on field survey data [7-10]. The passive-cooling process of cool alley is complex and dynamic. As a result, the studies cited above were not able to clearly describe this process.

In this study, we took a different approach in which we simulated the thermal environment of a typical ‘cool

alley' using the computational fluid dynamics (CFD) three-dimensional (3D) unsteady simulation method, rather than the steady simulation method, to reveal the dynamic passive-cooling process of the alley and quantitatively analysed the principles of this energy-saving design strategy (Section 2). Then, on the basis of the results of this study, we provide new ideas and methods for further study on the modern use of this strategy in architecture and urban planning (Section 3).

CFD is a branch of fluid mechanics that uses numerical methods and algorithms to solve and analyse problems that involve fluid flows. In this process, computers are used to perform the calculations required to simulate the interaction of liquids and gases with surfaces defined by boundary conditions [11]. With the rapid development of computer and numerical methods, CFD is currently widely used in the engineering field. It has obvious advantages over traditional field surveys, such as short cycles, low cost, and not being influenced by climate conditions. Most importantly, its simulation results can visually display temperature and velocity fields. Thus, CFD is one of the most advanced techniques for studying thermal environments.

## 2 Case study : the simulation of the thermal environment of traditional Shoujinliao residence

### 2.1 Physical model and problem statements

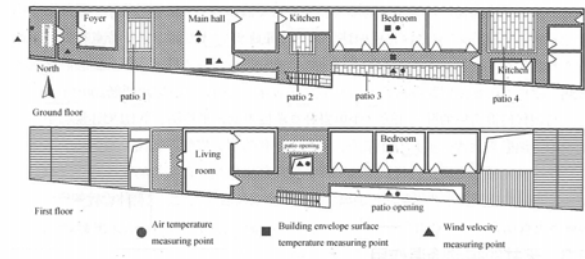
Shoujinliao is a type of traditional residence in southern areas such as Fujian province, Guangdong province, and Taiwan. The buildings normally have a width of 3–4 m and a depth of tens of meters with narrow cool alleys running between them.

The Shoujinliao residences at 112 Jubao Street in Quanzhou city, Fujian province (Fig. 3), have a width of 3.6 m and a depth of 44 m. The cool alleys (only 1 m wide) between the residences run parallel to the prevailing summer winds. Their aspect ratio is approximately 6:1.

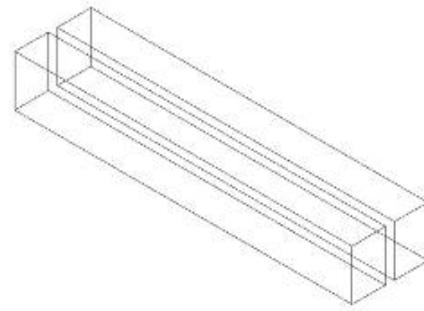
Quanzhou city, in which these residences are located, is located at latitude range  $24^{\circ} 30' - 25^{\circ} 56' N$  and longitude range  $117^{\circ} 25' - 119^{\circ} 05' E$ , and consequently has a subtropical oceanic climate with very hot, humid summers. The average temperature in July is  $28.6^{\circ}C$ . Further, the maximum average monthly temperature ever reached was  $32.9^{\circ}C$ . The average relative humidity in July is 80%, and the annual average humidity is 76%. The prevailing summer wind blows to the north and has an annual mean wind speed of 2.9 m/s [7].

We created a 3D physical model in AUTOCAD based on the actual floor plans. However, owing to the large size of the residence and limited computer capacity, we simplified the physical model to that shown in Fig. 4. The buildings on each side of the alley are 40 m long, 4 m wide, and 6 m high, and the alley is 40 m long, 1 m wide, and 6 m high.

In this study, we used the FLUENT software, and generated 3,795,766 unstructured computational grids in GAMBIT, a commercial software package.



**Figure 3.** A Soujinliao residence at 112 Jubao Street in Quanzhou city, Fujian province [7]



**Figure 4.** Physical model (Source: drawn by author)

### 2.2 Mathematical model

Because the passive-cooling process of cool alley is complex and dynamic, we simulated numerically the thermal environment of the Shoujinliao 'cool alley' under the most unfavourable condition (from 8:00 to 16:00) using a 3D unsteady simulation method.

We used the standard  $k-\varepsilon$  model and adopted the Pressure-Velocity coupling PIOS arithmetic to solve the equations. The discretization scheme used for momentum, turbulence kinetic energy, and turbulence dissipation rate was second order upwind.

The solved equations are outlined below:

Continuity equation

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \quad (1)$$

Momentum equation

$$\begin{aligned} \frac{\partial u}{\partial \tau} + \frac{\partial}{\partial x}(uu - v_{eff} \frac{\partial u}{\partial x}) + \frac{\partial}{\partial y}(uv - v_{eff} \frac{\partial u}{\partial y}) + \frac{\partial}{\partial z}(uw - v_{eff} \frac{\partial u}{\partial z}) = \\ - \frac{\partial p}{\partial x} + \frac{\partial}{\partial x}(v_{eff} \frac{\partial u}{\partial x}) + \frac{\partial}{\partial y}(v_{eff} \frac{\partial v}{\partial x}) + \frac{\partial}{\partial z}(v_{eff} \frac{\partial w}{\partial x}) \end{aligned} \quad (2)$$

$$\begin{aligned} \frac{\partial v}{\partial \tau} + \frac{\partial}{\partial x}(uv - v_{eff} \frac{\partial v}{\partial x}) + \frac{\partial}{\partial y}(vv - v_{eff} \frac{\partial v}{\partial y}) + \frac{\partial}{\partial z}(vw - v_{eff} \frac{\partial v}{\partial z}) = \\ - \frac{\partial p}{\partial y} + \frac{\partial}{\partial x}(v_{eff} \frac{\partial u}{\partial y}) + \frac{\partial}{\partial y}(v_{eff} \frac{\partial v}{\partial y}) + \frac{\partial}{\partial z}(v_{eff} \frac{\partial w}{\partial y}) \end{aligned} \quad (3)$$

$$\frac{\partial w}{\partial \tau} + \frac{\partial}{\partial x}(wu - v_{eff} \frac{\partial w}{\partial x}) + \frac{\partial}{\partial y}(wv - v_{eff} \frac{\partial w}{\partial y}) + \frac{\partial}{\partial z}(ww - v_{eff} \frac{\partial w}{\partial z}) = -\frac{\partial p}{\partial z} + \frac{\partial}{\partial x}(v_{eff} \frac{\partial u}{\partial z}) + \frac{\partial}{\partial y}(v_{eff} \frac{\partial v}{\partial z}) + \frac{\partial}{\partial z}(v_{eff} \frac{\partial w}{\partial z}) \quad (4)$$

Where  $v_{eff}$  was calculated from

$$v_{eff} = \frac{1}{R_e} + v_t \quad (5)$$

Transport equations for standard  $k - \varepsilon$  model are as follows:

For turbulence kinetic energy  $k$

$$\frac{\partial k}{\partial \tau} + \frac{\partial}{\partial x}(uk - \Gamma_{k,eff} \frac{\partial k}{\partial x}) + \frac{\partial}{\partial y}(vk - \Gamma_{k,eff} \frac{\partial k}{\partial y}) + \frac{\partial}{\partial z}(wk - \Gamma_{k,eff} \frac{\partial k}{\partial z}) = \nu_t \left[ 2 \left[ \left( \frac{\partial u}{\partial x} \right)^2 + \left( \frac{\partial v}{\partial y} \right)^2 + \left( \frac{\partial w}{\partial z} \right)^2 \right] + \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right)^2 + \left( \frac{\partial v}{\partial z} + \frac{\partial w}{\partial y} \right)^2 + \left( \frac{\partial w}{\partial x} + \frac{\partial u}{\partial z} \right)^2 \right] - \sigma_k \frac{k^2}{\nu_t} \quad (6)$$

Where the  $\nu_t$  and  $\Gamma_{k,eff}$  were calculated from

$$\nu_t = \frac{\sigma_k k^2}{\varepsilon} \quad (7)$$

$$\Gamma_{k,eff} = \frac{1}{R_e} + \frac{\nu_t}{\sigma_k} \quad (8)$$

For turbulence kinetic dissipation rate  $\varepsilon$

$$\frac{\partial \varepsilon}{\partial \tau} + \frac{\partial}{\partial x}(u\varepsilon - \Gamma_{\varepsilon,eff} \frac{\partial \varepsilon}{\partial x}) + \frac{\partial}{\partial y}(v\varepsilon - \Gamma_{\varepsilon,eff} \frac{\partial \varepsilon}{\partial y}) + \frac{\partial}{\partial z}(w\varepsilon - \Gamma_{\varepsilon,eff} \frac{\partial \varepsilon}{\partial z}) = \sigma_{\varepsilon} \sigma_k k \left[ 2 \left[ \left( \frac{\partial u}{\partial x} \right)^2 + \left( \frac{\partial v}{\partial y} \right)^2 + \left( \frac{\partial w}{\partial z} \right)^2 \right] + \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right)^2 + \left( \frac{\partial v}{\partial z} + \frac{\partial w}{\partial y} \right)^2 + \left( \frac{\partial w}{\partial x} + \frac{\partial u}{\partial z} \right)^2 \right] - \sigma_{\varepsilon} \frac{\varepsilon^2}{k} \quad (9)$$

Where the  $\Gamma_{\varepsilon,eff}$  was calculated from

$$\Gamma_{\varepsilon,eff} = \frac{1}{R_e} + \frac{\nu_t}{\sigma_{\varepsilon}} \quad (10)$$

The constants in the standard  $k - \varepsilon$  model were listed in Table 1.

Energy equation

$$\frac{\partial T}{\partial \tau} + \frac{\partial}{\partial x}(uT - K_{eff} \frac{\partial T}{\partial x}) + \frac{\partial}{\partial y}(vT - K_{eff} \frac{\partial T}{\partial y}) + \frac{\partial}{\partial z}(wT - K_{eff} \frac{\partial T}{\partial z}) = 0 \quad (11)$$

Where  $K_{eff}$  was calculated from

$$K_{eff} = \frac{1}{\rho_f R_e} + \frac{\nu_t}{\sigma_T} \quad (12)$$

## 2.3 Boundary conditions

### 2.3.1 Inlet boundary condition

The velocity of the approaching wind is 0.3 m/s, which is the mean wind velocity at the entrance of the same alley measured by researchers [7]. A UDF was used to define the temperature of the inlet, which changed with time.

### 2.3.2 Outlet, Sides and Top boundary condition

The outlet port is far from the buildings; therefore, we assumed that the flow through the outlet port developed fully and the normal gradient of all variables is zero. Consequently, the outflow boundary was applied.

**Table 1.** The constants in the standard model.

Model	$\sigma_1$	$\sigma_2$	$\sigma_{\mu}$	$\sigma_k$	$\sigma_{\varepsilon}$	$\sigma_T$
<b>Standard</b>						
$k - \varepsilon$ Model	1.44	1.92	0.09	1.00	1.30	0.90

### Nomenclature

$u, v, w$	$x, y, z$ velocity component	$x, y, z$	Cartesian coordinates
$k$	Turbulence kinetic energy	$v_{eff}$	Turbulent effective viscosity
$\varepsilon$	Turbulence energy dissipation rate	$\Gamma_{k,eff}$	Effective diffusion coefficient for turb. kinetic energy
$\nu_t$	Turbulent viscosity	$\Gamma_{\varepsilon,eff}$	Effective diffusion coefficient for turb. energy dissipation rate
$\sigma_1, \sigma_2, \sigma_{\mu}$	Constants in the standard $k - \varepsilon$ model	$\sigma_k, \sigma_{\varepsilon}, \sigma_T, C_{\mu}$	Constants in the standard $k - \varepsilon$ model

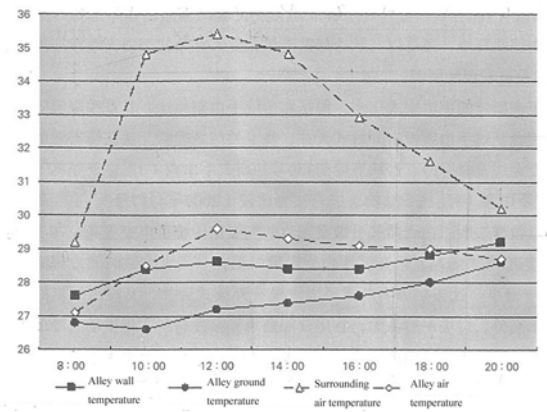
Like the outlet and inlet ports, the side and top boundaries are not the real physical boundaries; therefore, we made assumptions about their boundary conditions. In this case, the computing domain was sufficiently large and the approaching wind direction was horizontal. Further, the side and top boundaries were far from the surfaces of the walls. Therefore, we assumed that both the velocity gradient at a tangent and the normal gradient were zero.

### 2.3.3 Wall boundary conditions and UDFs

According to the field survey data of the same alley presented by Chen et al. [7], UDFs were used to define the temperature of the walls and ground in the alley, which also changed with time.

Temperature-time curves of the walls, the ground, and the air temperature in the alley based on a field study by Chen et al. [7] (8:00–20:00, July 15, 2009), are shown in Fig. 5. The curves were divided into several time segments (specifically, 8:00 – 10:00, 10:00 – 12:00, 12:00 – 14:00, and 14:00 – 16:00) and the linear equations of each curve segment defined. Then, the mathematical equations were translated into functions written in the C programming language. The UDFs were subsequently applied to the FLUENT model.

In the study, the simulation time was from 8:00 to 16:00. We set 16 time steps, each comprising 1800 s. The iteration of each time step was converged, with a convergence criterion of  $10^{-6}$ . The computation results of each time step were used as the initial values of the ensuing step. The final simulation results were verified against the field survey data presented by Chen et al. [7].



**Figure 5.** Temperature-time curves of the walls, ground, and the air in the alley based on the field study by Chen et al [7].

## 2.4 Results and discussion

The temperature contours in Figs. 6–11 show the respective temperatures at a height of 1.5 m in the alley at 8:30, 9:00, 10:00, 12:00, 14:00, and 16:00.

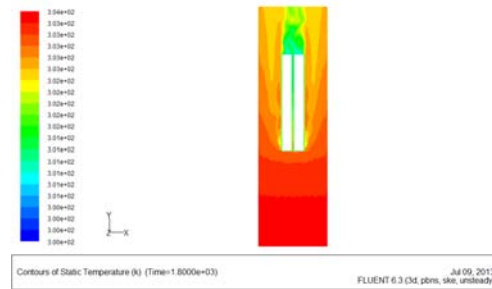
From the analytical results in Table 2, it is clear that from 8:00 to 16:00, the air temperature in the alley remained lower than that of the surrounding air, with temperature difference ranging from 2.1 °C to 3.6 °C.

Chen and Zhong [10] investigated the main reasons for this cooling effect. Their results indicate that, in summer, because of the cold storage process of the walls and ground at night and the sun-shading effect of the buildings in the daytime, the temperature of the walls and ground in the alleys is lower than the air temperature in the alleys, leading to their heat storage process, in which they absorb the heat from the air and then reduce its temperature. As a result, the air temperature in the alleys remains lower than the surrounding air temperature during the daytime.

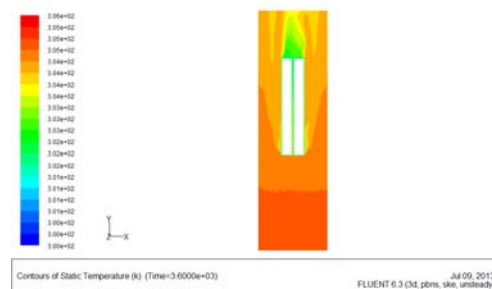
When the warm indoor air of the rooms rises and flows outdoor, the cool outdoor air in the alleys naturally flows indoors through the doors and windows to compensate, providing a good ventilation path and reducing the indoor temperature.

## 2.5 Verification of simulation results

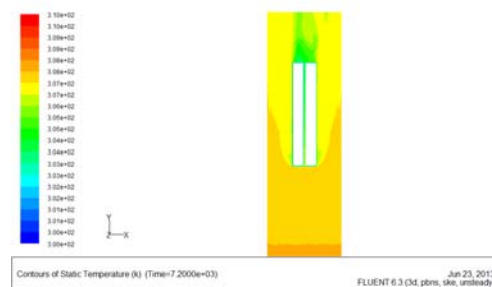
The results of the simulation were verified by comparing them to the field survey data of the same alleys presented by Chen et al. [7]. The results of the comparison are shown in Table 3. From Table 3, it is clear that the simulation results are congruent with the measured results and the error is small.



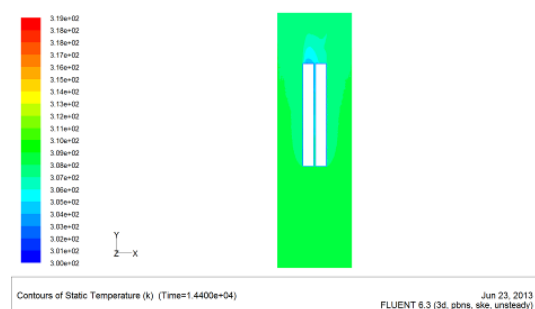
**Figure 6.** The temperature contours at 8:30 created at the height of 1.5m in Shoujinliao cool alley



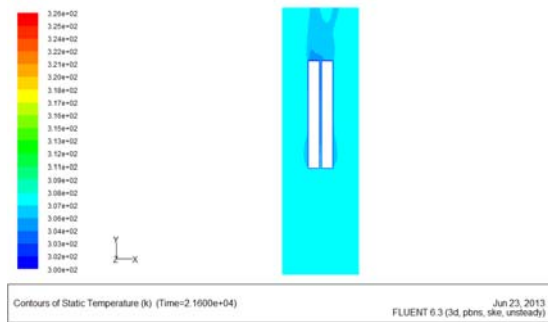
**Figure 7.** The temperature contours at 9:00 created at the height of 1.5m in Shoujinliao cool alley



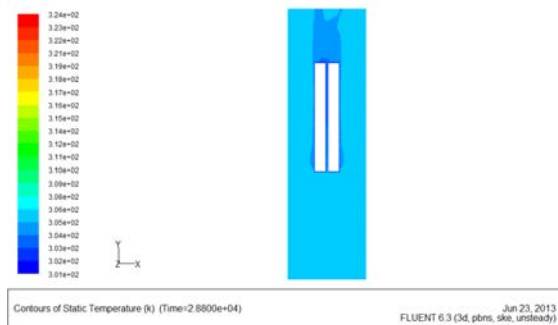
**Figure 8.** The temperature contours at 10:00 created at the height of 1.5m in Shoujinliao cool alley



**Figure 9.** The temperature contours at 12:00 created at the height of 1.5m in Shoujinliao cool alley



**Figure 10.** The temperature contours at 14:00 created at the height of 1.5m in Shoujinliao cool alley



**Figure 11.** The temperature contours at 16:00 created at the height of 1.5m in Shoujinliao cool alley

**Table 2.** Simulation results for the temperature of the walls, ground, and air in the alley

Time	Measured ground temp. (°C)	Measured wall temp. (°C)	Measured surrounding air temp. (°C)	Simulated air temp. in the alley (°C)	Temp. difference (°C)	Temp. contour figures
9 :00	26.7	28.0	32.0	29.9	2.1	Fig. 7
10 :00	26.6	28.4	34.9	31.4	3.5	Fig. 8
12 :00	27.2	28.6	35.4	32.0	3.4	Fig. 9
14 :00	27.4	28.4	34.8	31.2	3.6	Fig. 10
16:00	27.6	28.4	33.0	30.0	3.0	Fig. 11

### 3. Conclusions

The simulation results prove that the cool alleys do have a temperature-reducing effect and played a very important role in improving the microclimate of historic settlements. They also prove that CFD is an effective and reliable method for studying the thermal environment of cool alleys. In the study, we found that different wall and ground materials and design parameters will have different effects on the cooling efficiency of cool alleys. Therefore, our next step will be to study the effect of various wall and ground materials on the cooling efficiency of cool alleys and try to optimize the various design parameters such as the high aspect ratio and length of the cool alley and the dimensions of the patio connecting to it. We believe that our research findings will help to promote modern use of this traditional energy-saving design strategy in architectural design and urban planning.

### Acknowledgement

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**Table 3.** Comparison of simulation results to measurement data from Chen et al. [7]

Time	Measured surrounding air temperature (°C)	Measured air temperature in the alley (°C)	Simulated air temperature in the alley (°C)	Error size
9:00	32.0	28.0	29.9	6.0%
10:00	34.9	28.5	31.4	10.0%
12:00	35.4	29.6	32.0	8.0%
14:00	34.8	29.3	31.2	6.5%
16:00	33.0	29.1	30.0	3.0%

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