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Numerical analysis of a vertical double-pipe single-flow heat exchanger applied in an active cooling system for high-power LED street lights

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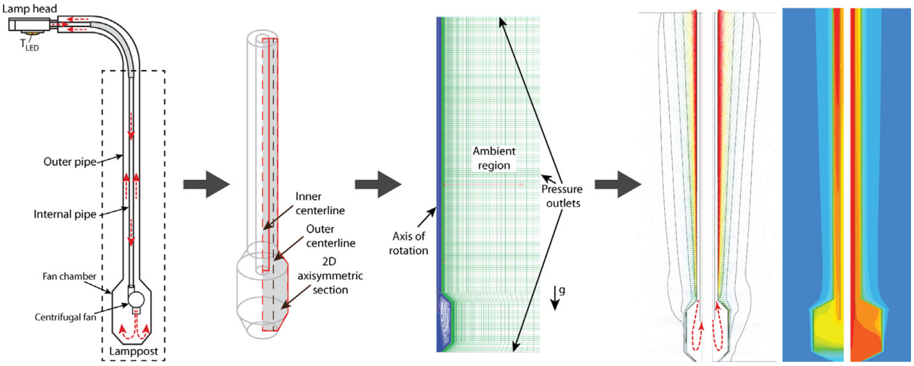
HIGHLIGHTS

- Active air cooling system for high-power LED street lights is analyzed.
- Heat is dissipated from the lamp post by natural convection.
- Axisymmetric numerical simulation using ANSYS Fluent has been performed.
- Center-In-Side-Exit (CISE) flow configuration has shown higher heat transfer rates.
- Effect of thermal conductivity of center pipe material is less than 3%.

GRAPHICAL ABSTRACT



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ABSTRACT

The present study examines the use of a vertical double-pipe single-flow heat exchanger as part of an active air cooling system for a 150 W LED street light. The air is circulated inside the lamppost by an internal fan to form a closed-loop system. The heat is dissipated to the surrounding air by natural convection, reaching Rayleigh numbers up to $Ra = 6.5 \times 10^{10}$. Experiments with a 5 m high prototype were conducted, and the data were used to validate the numerical model. The experimental results show that the LED excess temperature can be lowered to about 42 °C. A two-dimensional axisymmetric numerical simulation was performed to study the influence of various parameters, including pipe length, material conductivity, flow direction, pipe diameter ratio, and mass flow rate, on the heat transfer rate. The findings show that the additional heat loss created by extending the lamppost largely depends on the flow rate. When extending the lamppost from 3 to 5 m at a high mass flow rate of 0.014 kg/s, the heat loss increases by 34.1% to 120.2 W. The numerical study was also used to visualize the hydrodynamic boundary layers on the surface of the lamppost and the temperature contours in and outside of the heat exchanger.

1. Introduction

Light emitting diodes (LED) are gradually replacing traditional light sources in commercial and residential sectors. As well as higher energy efficiency, LEDs have a longer lifetime, often advertised up to 50,000 h, which is about 50 times longer than incandescent and 4–5 times longer than fluorescent light sources [1]. One of the main challenges in designing LED applications is ensuring adequate thermal management to remove and dissipate the heat produced by the LED and to guarantee reliable and safe operation. High temperatures can damage the p-n junction, lower the luminous efficiency, shift the wavelength, and reduce the quantum efficiency of phosphor, which all negatively affect the lifetime of the

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Nomenclature

A	flow cross section (m^2)
c_p	thermal heat capacity (J/kg K)
D	diameter of lamppost (m)
f	friction factor
Gr_L	Grashof number
g	gravitational acceleration (m/s^2)
k	turbulent kinetic energy (m^2/s^2)
L	length of inner pipe (m)
$\dot{m}$	mass flow rate (kg/s)
Nu_L	Nusselt number
$\dot{Q}$	heat loss (W)
Ra_L	Rayleigh number
T	temperature (K)
u, v, w	velocity in different directions (m/s)

Subscripts

a	ambient
c	center
exp	experimental
FC	fan chamber
ip	inner pipe
j	junction
num	numerical
op	outer pipe
out	outlet
s	surface

Greek symbols

β	volume expansion coefficient (1/K)
Γ	generalized diffusion coefficient
ε	dissipation rate of turbulence (m^2/s^3)
μ	dynamic viscosity (kg/m s)
μ_t	turbulent dynamic viscosity (kg/m s)
ν	kinematic viscosity (m^2/s)
ν_t	turbulent kinematic viscosity (m^2/s)
ρ	density (kg/m^3)

Acronyms

Al	aluminum
CISE	Center-In-Side-Exit flow
Fg	fiberglass
GHE	ground heat exchanger
LED	light emitting diode
PVC	polyvinyl chloride
SICE	Side-In-Center-Exit flow

LED [2]. The maximum allowable junction temperature (T_j) for safe operation varies among manufacturers, but is in the range of 120–140 °C. However, lower temperatures are desirable because they severely influence the lifespan of LEDs, as an increase in T_j of 10–15 °C can reduce the lifetime by 50% [3].

Most studies on thermal management of LEDs have focused on the design and optimization of passive heat sinks [4–8], which are often combined with heat pipes [9–11] or vapor chambers [12,13] to improve the thermal performance by reducing the spreading resistance. Two recent studies found that perforations [8] or opening slits [5] on the base of free-hanging oversized heat sinks can increase the air flow through the fin array and reduce the thermal resistance by up to 30.5% and 36.7%, respectively. Ye et al. [10] designed a heat sink with parallel vertical fins and three embedded heat pipes for high-power LED applications. Experimental and numerical analyses were carried out to investigate the optimal fin spacing to achieve the smallest thermal resistance. The experiments with an 80 W LED showed that the optimized design can limit the temperature of the heat sink base to about 70 °C. While passive cooling systems are extremely reliable and do not require additional power consumption, they are usually limited to power inputs of less than 100 W. Active cooling solutions, such as forced air [14–19] or liquid cooling systems [20–22], are more capable of maintaining the junction temperature of high-power LEDs under a critical limit. Deng et al. [14] conducted an experimental evaluation of single-and dual-synthetic jet actuators combined with a heat sink. The system consumed about 3.2 W of power and was used to cool a 30 W LED chip. The results showed that the single-synthetic jet actuator could maintain the base temperature at 46.5 °C and the double jet could reduce it by 4 °C. Synthetic jets can be integrated in very compact systems, but for higher power ranges, fans have a better overall heat dissipation capability. Geisler [15] developed an active thermal solution consisting of multiple fans combined with a densely folded copper heat sink. His design could maintain a dummy heater with a 600 W input at a base excess temperature over ambient of 85 °C. Iaronka et al. [16] designed and investigated a closed-loop forced air cooling system for high-power LED street lamps. The system was driven by five axial fans, which were arranged on top of a heat sink inside an aluminum housing, from which the heat is dissipated by natural convection to the surroundings. Their results showed that the cooling system can reduce the temperature of a 68 W LED by up to 27.9 °C, compared to a case with only the heat sink. The main drawback of this design is that the hot internal air is contained inside the housing and only the lamp head case acts as an external cooling body. Liquid cooling systems are more complex than forced air cooling systems, but they can provide higher cooling capacities. They usually consist of a cold plate attached to the LED, a reservoir to store the liquid, a pump to drive it, and a liquid-to-air heat exchanger to dissipate the heat to the surroundings. Ramos-Alvarado et al. numerically compared multiple cold plates with different microchannel designs [23] and, in a subsequent study, applied the best cold plate design to an array of 64 high-power LEDs with various power inputs and flow rates [20]. Their simulations showed a T_j of about 80 °C at a total input power of 192 W and a pumping power of 1 W. However, the study considered an array of individual LEDs instead of single high-power LED chip, and the pumping power of 1 W is only derived from the numerical pressure drop across the cold plate and does not represent the complete cooling system.

The present study analyzes a novel forced-air cooling system for LED street lights, which uses the lamppost as an air-to-air heat exchanger to dissipate heat to the surrounding air. The air-flow inside the lamppost is driven by an internal fan, and the whole system is sealed to prevent dust and debris from entering the system; this reduces maintenance cycles, lowers the risk of system failure, and thus makes it especially suitable for extreme climatic conditions. This type of vertical single-flow double-pipe heat exchanger has a similar working principle to coaxial ground heat exchangers (GHEs) [24–29]. However, the aim is not to transfer the heat from one pipe to the other, as in conventional double-pipe heat exchangers with two inlets and outlets [30], but rather to transfer it through the outer pipe wall to the surrounding air. According to the experimental findings of Jalaluddin et al. [24], coaxial GHEs have a 61% higher heat exchange rate than U-tube GHEs at a depth of 20 m and a flow rate of 4 l/min. In fact, Acuna and Palm [27]