LED professional
www.led-professional.com
ISSN 1993-890X

Review

LpR

The leading worldwide authority for LED lighting technology information

May/June 2011 | Issue 25

LED Cooling in Harsh Environments with Synthetic Jet Technology

LED Cooling in Harsh Environments with Synthetic Jet Technology

Dr. Markus Schwickert, Director of Reliability and Brandon Noska, Application Engineering Manager at Nuventix discuss different reliability issues of active cooling. Test procedures and results to prove longevity of sophisticated active cooling systems are presented.

Lighting is rapidly transitioning from traditional lamp sources such as high-pressure sodium, metal halide, mercury vapor, and fluorescent to high brightness light-emitting diodes (HB LEDs). In fact, illumination was the second fastest growing application for HB LEDs in 2009, with a growth rate of 28.6% over 2008, and this trend shows no signs of slowing. Architectural lighting, combined with commercial/industrial sectors and the outdoor sector, account for 54.3% of the illumination market [1].

Along with general illumination products, LED outdoor lighting needs proper thermal management in order to utilize the many advantages of LEDs such as a long L70 lifetime, instant on, better optical control, and, most importantly, low maintenance and reduced energy usage. Outdoor products cover a wide range of installations including wall washing, parking lot, area lighting, roadway lighting, and garage lighting, to name a few. Some of these form factors have enough surface area to allow for effective natural convection cooling, but pose other issues such as weight and large surfaces which are not good for shipping, handling, installation, and wind loading. Other form factors such as retrofit lamps are bound by existing infrastructure and need to remain compact in order to fit into existing sockets. In all cases, if a reliable technology for forced convection cooling was available, designers would have more options to provide the proper lumen outputs while having small, lightweight designs.

Industrial and outdoor applications pose other challenges in addition to the thermal management requirements. Components need to be rugged in order to operate properly and to survive the elements. Although traditional air movers such as axial fans could provide an adequate forced convection thermal solution, this article will focus on synthetic jet cooling technology, which is an alternative air moving technology for forced convection cooling. This article looks at synthetic jet technology as a rugged and reliable forced convection cooling solution that could be used in harsh environments to ensure effective thermal management solutions.

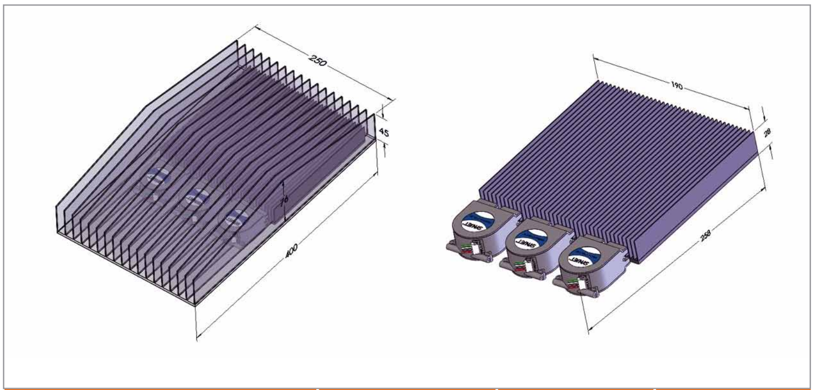
Synthetic Jets

Although synthetic jets have been known and researched for many years, synthetic jet products are relatively new to the market. Synthetic jets are formed by creating a periodic suction and ejection of fluids through an orifice generated by an oscillating diaphragm in a cavity surrounding the diaphragm. The jets are "zero-mass-flux," thus there is no need for ducting or piping in the medium for cooling. When these jets are directed at heat sink surfaces, they remove the heat much more efficiently than natural convection [2,3,4].

Figure 1: Synthetic jet engine with oscillating diaphragm

Synthetic jets can be generated in many ways, but one mechanism is the use of electromagnet actuators which create the driving force for oscillating the membrane. As the membrane oscillates within the cavity, synthetic jets are created at the nozzles that are around the cavity. There are many advantages to using electromagnetic actuators including no moving parts in friction, no lubricants, and no bearings to wear out. These inherent design differences between synthetic jets and traditional air movers such as fans and blowers are what differentiate these products in terms of ruggedness and

Figure 2 / Table 1: Natural convection versus forced convection. The table shows comparison data for natural convection versus forced convection



Metric	Natural Convection	Forced Convection	Improvement
Form Factor Volume, cm^3	5640	1400	75%
Weight (kg)	3.0	1.4	53%
Thermal performance θ_{sa}, C/W	0.25	0.2	20%

lifetime. The main failure mode of fans and blowers is lubricant breakdown. This does not exist in synthetic jet products [5,6].

Benefits of Forced Cooling

Synthetic jet cooling allows for smaller form factors, lower operating temperatures, and dynamic airflow control for effective temperature control of the LED heat sink.

Synthetic jets have been shown to have higher Nusselt numbers, hence higher effective heat transfer, over conventional ducted flows by a factor of six or greater at the same channel Reynolds number. In addition, when comparing the thermal resistance of a heat sink ($\theta_{s\text{-}a}$) cooled by synthetic jets or ducted flow at the same volumetric flow rate, synthetic jets have demonstrated as much as a 40% improvement in thermal performance. When compared to natural convection, synthetic jets have demonstrated 300% thermal improvement with the same form factor heat sink [7].

The higher heat transfer capability at low flow and significant improvement over natural convection is due to the turbulent vortex dominated jet flow which enhances the mixing of the thermal boundary layer and allows for improved thermal performance. For example, Figure two compares a 100 W design with forced convection cooling and natural convection cooling.

The forced convection coolin provides a 20% reduction in thermal resistance resistance (qs-a), with a 75% reduction in volume and 53% reduction in weight.

The Evluma 40 W LED replacement lamp / luminaire for outdoor NEMA Type 5 fixtures is an example of a synthetic-jet cooled product available on the market today. This product replaces existing mogul base 50-175 W mercury vapor or 70-150 W high pressure sodium lamps. Evluma's 40 W LED lamp is an example of a product that utilizes forced cooling to dissipate 40 W, while keeping the form factor small for retrofit applications.

Figure 3: Evluma's 40W LED Clearlight

Although the use of forced cooling has many benefits as listed above, there are several elements that need to be considered for outdoor lighting. Typical requirements include IP 55 for electronics and other components, IP 67 for optical compartments, ability to withstand wash downs, to be cleaned, large temperature extremes, vibration due to wind loading and roadway vibrations. An effective outdoor LED light requires components that can withstand such elements. Synthetic jets offer a rugged and reliable solution. Synthetic jets are typically tested against high temp/high humidity, shock/vibration, dust, and power cycling [8].

The next sections highlight the various testing that is conducted on synthetic jet devices and the importance of this testing:

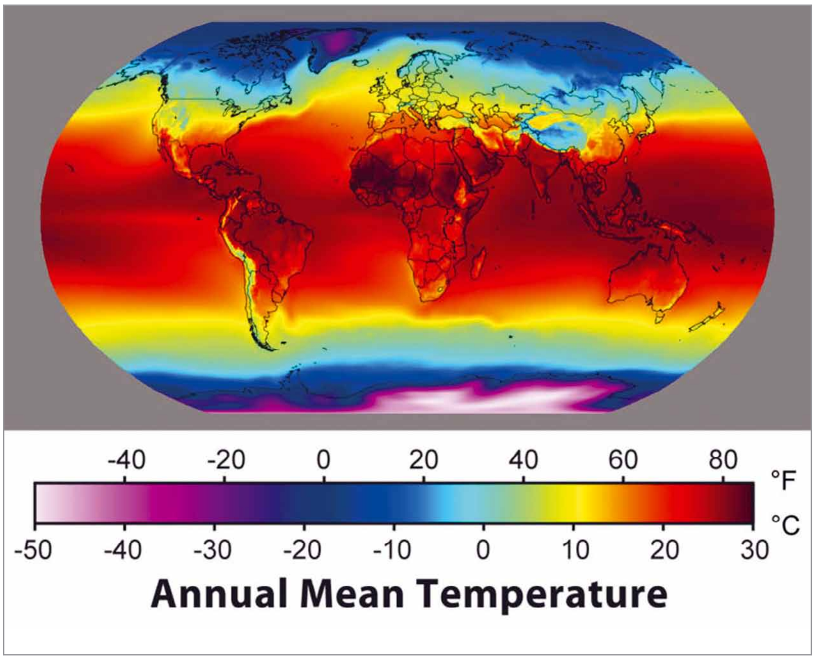


Figure 4: Annual average temperature map, source Wikipedia.org

Reliability

The local environment of a cooling solution in an outdoor light fixture depends very much on the construction of the enclosure and the location and orientation of installation. Earth atmospheric temperatures typically range from -40°C to +40°C and can reach over +55°C in extreme conditions. Variations occur in day/ night cycles and throughout the seasons while the relative humidity (r.h.) can range from nearly 0 to 100%.

Furthermore, pollution (e.g. acidic atmospheres, pesticides, cleaning solutions, building materials), ozone, UV light, and naturally occurring substances in the atmosphere (e.g. dust, pollen, insects) will interact with light fixtures and may reach internal components such as the LEDs, electronics, drivers and cooling solutions, impacting functionality or lifetime. Generally, harsh environments can not only be found outdoors, but in some industrial settings or specialty applications (e.g. aquariums, commercial kitchens, automotive etc.) as well.

Even ratings for ingress protection (IP) will not reveal how the lifetime of a product is affected by harsh environments, but rather testify to its safety and ability to function under those conditions in the short term. Here we focus on the cooling solution of a luminaire which must exceed the lifetime of the LEDs by far so that it contributes positively to the overall lifetime of the luminaire via extension of the LED lifetime, and does not limit it further [9].

Given the unique requirements for all different products and environments, there is no standard or set regiment of testing that can guarantee outdoor suitability across the board. Moreover, a robust product with reliability designed in must be measured up to the intended usage environments from the early design phase through the production release. A thorough review and qualification of the subcomponents, materials and even processes used in manufacturing is a must when designing for reliability.

As a result, the latest SynJet family of products, synthetic jets commercialized by Nuventix, has eliminated all structural adhesive joints, and all materials and components must pass a 60 hour autoclave test (Highly Accelerated Stress Test, HAST) at 123°C, >95% r.h. and 2 atmospheres pressure.

With input from numerous customers who inquired about outdoor usage, Nuventix has developed a platform-based comprehensive qualification test matrix for synthetic jet products that helps in predicting long-life performance under all realistic conditions, some of which are discussed below.

Freezing Rain Cycle Test

This cyclic test is designed to address the repeated wetting and freezing of a product. In an environmental test chamber the test starts at standard ambient temperature (+25°C) with >95% r.h. followed by a sudden drop to -10°C to condense water on the unit and freeze it. After 10 minutes of freezing the unit is powered on for five minutes and then operation is validated. This is repeated a minimum of 100 times.

Thermal Cycling

Thermal cycling, besides exposing the materials to a wide temperature range, addresses designs with mismatched coefficients of thermal expansion (CTE) and stresses joints and material properties. By going 200 times or more between -40°C and +105°C, soaking for an hour at each temperature and ramp rates of 5°C/ minute with no failures allowed, this test adds to the confidence needed for a robust product in harsh conditions.

Humidity

The effects of high temperature and high humidity can be surprising. Two major areas are affected: plastic material degradation and metallic corrosion. All synthetic jet types are tested for a minimum of 2,000 hours at 85°C and 85% r.h. with no failures allowed.

Cyclic Condensing Humidity

Very hot and humid conditions are not as realistic as cyclic humidity conditions with condensation which can be achieved by cooling a device and then subjecting it to warmer, humid air (similar to taking a water bottle out of a refrigerator which will typically condense a lot of water from a sufficiently humid atmosphere). During the morning hours in most outdoor environments, depending on heat capacity and heat conduction of an object, condensation will be found on its surface. Repeating this process with subsequent drying 200 or more times in a laboratory environment will bring out material and design weaknesses associated with condensing humidity.

HALT

Highly Accelerated Life Testing uses a combination step stress method to determine the margins of operation for a product and highlights weak links in a design. Stressors include cold and hot thermal stress as well as mechanical vibration stress. Table 2 shows an example of SynJet limits as determined by HALT.

Qualification Matrix

Table 3 shows a summary of tests that were done and passed with the latest synthetic jet family of products. Besides conditions, Table 3 also indicates the sample size that was used in the test.

Conclusion

Forced convection cooling can offer smaller and lighter weight designs while maintaining the proper thermal management needed to keep HB LEDs within their design parameters. Synthetic jet technology is an air-moving technology for forced convection cooling that is inherently reliable and rugged due to a construction that does not have moving parts in friction or require bearings or lubricants. Synthetic jet products are subjected to a rigorous qualification program to ensure the products are robust and can handle a wide application space.

Figure 5: **Synthetic jet undergoing freezing rain cycle test**

Finally, there is no exact test that can predict performance and reliability under all environmental conditions for every conceivable luminaire design. However, by simulating worst case specific environmental conditions that occur during the expected life of an HB LED light and using accelerated stress tests for anticipated failure modes one can gain confidence in applications in harsh environments.

Table 2: **HALT operating and destruct limits**

Summary of Operating and Destruct Limits

Stress Type	Chamber Setpoint Level
Temperature Lower Operating Limit (LOL)	-60°C
Temperature Lower Destruct Limit (LDL)	< -100°C
Temperature Upper Operating Limit (UOL)	+120°C
Temperature Upper Destruct Limit	> +130°C
Thermal Transitions (°C)	Greater than +50°C/minute
Vibration Operating Limit (OL)	45 Grms
Vibration Destruct Limit (DL)	45 Grms
Combined Operating Limit (OL)	60 Grms and 115°C to -60°C
Combined Destruct Limit (DL)	65 Grms and -60°C

Table 3: **The qualification matrix shows a summary of tests including the sample size**

Cat.	Test	Operating	Conditions	Samples
Storage	HAST	no	60 hours at 123°C, 96% r.h., 2 atmospheres	3
	Low Temperature	no	-40 °C	11
Operational	Accelerated Life Testing	yes	3,300 hours at 105°C	540
	Life Testing at max normal	yes	9,000 hours at 85°C, ongo-ing	75
	Low Temperature	yes	-40°C	87
	Humidity	yes	85°C/85% r.h., 3,250 hours	60
	Thermal Cycling	yes	-40°C - +105°C, 200x	60
Mechanical	Sine Sweeping	no	5-150 Hz, 2G 3 sweeps per axis	18
	Sine Dwelling	no	10 min each top of three peaks, 5 G	18
	Random Vibration	yes	2.2 G_{rms}, 20 min. each axis	18
	Shock	no	Six half-sine shocks per direction, 40 G, 11 ms	18
	Bump Test	-	1,000 shocks, 25 G, 10 ms	18
Environmental	Dust	yes	12 hours IEC 60529 (IP5X)	4
	Cyclic humidity	yes	200 cycles between +50°C / >95% r.h. and +5°C / 5% r.h., such that condensation occurred	22
	Freezing Rain Cycles	yes	100 cycles between +25°C / 95% r.h. and –10°C / u.c.r.h.	21

References:

[1] Strategies Unlimited, "High-Brightness LED Market Review and Forecast 2010", pp. 78- 83, June 2010

[2] Lasance, Clemens J. M., Aarts, Ronald M., "Synthetic Jet Cooling Part I: Overview of Heat Transfer and Acoustics", 24th IEEE SEMI-THERM Symposium, 2008, pp. 20-25, 2008

[3] Mahalingam, R., N. Rumigny, A. Glezer, "Thermal Management Using Synthetic Jet Ejectors", IEEE Trans on Components and Packaging Technologies, Vol. 27, No. 3, pp. 439-444, 2004

[4] Mahalingam, R., A. Glezer, "Design and Thermal Characteristics of a Synthetic Jet Ejector Heat Sink", Journal of Electronic Packaging, Vol. 127, pp. 172-177, 2005

[5] Mahalingam, R., S. Heffington, L. Jones, R. Williams, "synthetic jets for forced air cooling of electronics", Electronics Cooling, Vol. 13, No. 2, 2007

[6] Tian, Xijin, "Cooling Fan Reliability: Failure Criteria, Accelerated Life Testing, Modeling and Qualification", Annual Reliability and Maintainability Symposium, 2006, pp. 380-384, 2006

[7] Noska, B., Che Cheung Jin, H. Mahalingam, R., "Enabling new LED designs through advanced cooling technology", Semiconductor Thermal Measurement and Management Symposium, 2010, SEMI-THERM 2010. 26th Annual IEEE, pp. 305-310

[8] http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/outdoor_area_lighting.pdf

[9] Schwickert, M. M., IEEE Transactions on Reliability, pp. 449-482, Volume 59, Number 3, September 2010

