# A Liquid Air Economy

## Why Liquid Air?

A liquid air economy has many benefits. Liquid air can be made anywhere, no need to mine it, no need to refine it, it is non-polluting, relatively safe, and it can be made at low cost with SuperHero Claude cycle liquefiers.

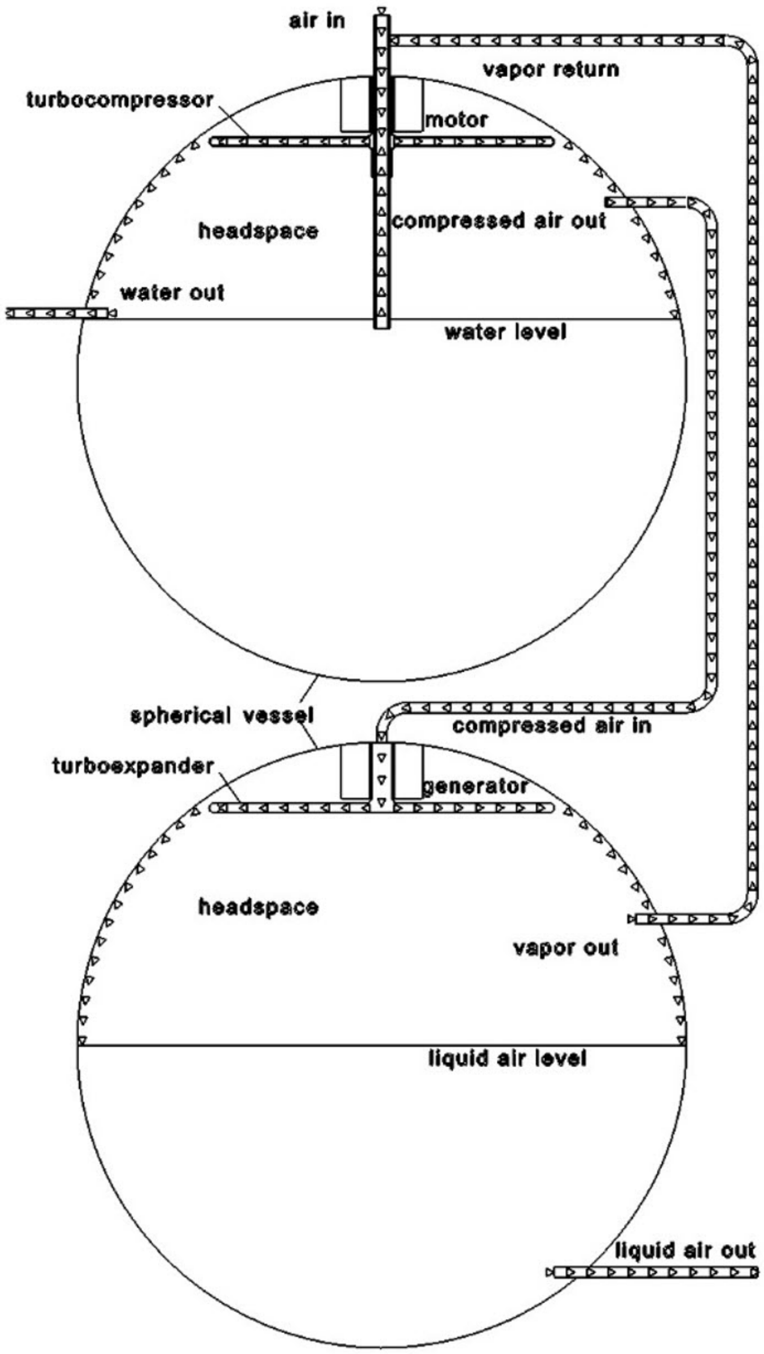


**Fig. 1 SuperHero Claude Cycle Compressor and Liquefier Schematic**

The motor driven SuperHero turbomachine in the upper spherical container in Fig.1 uses recirculating water as a periodic liquid piston to provide near isothermal air compression.

The compressed air from the upper spherical container can be expanded in the lower spherical container by a SuperHero expander turbine to liquify the air in a Claude cycle.

Liquid air can provide short-term and long-term storage for intermittent sources including photovoltaics and wind. Liquid air storage does not require pressurization.

Liquid air is attractive as a "utility". It is cheaper to distribute liquid air in a district or a building for air-conditioning, air make up, compressed air, refrigeration, electricity production, fan operation, electronics cooling, and electronics powering, than to provide these services individually. Liquid air can be supplied via a recirculating loop manifold. Personalized cool, clean fresh air can be provided at low cost and with low noise. Heat can be added via electricity from SuperHero liquid air turbogenerators.

Compressed air is an attractive utility and would enjoy greater use with greater access. Superhero turbomachines can provide quiet compressed air at low cost. Compressed air can be provided by SuperHero liquid piston recirculating water air compressors, by liquid air ported to a storage vessel, closed off from the liquid air supply vessel and heated by the local atmospheric to evaporate and thereby pressurize the air in a compressed air storage vessel, by a pump made from a pair of check balls with a heat exchanger between, and by liquid air pumps with downstream heat exchangers.

Liquid air can be transported by pipelines, trucks, trains, planes, and ships. Storage can be refilled as needed.

Liquid air allows existing fuel stations to become liquid air stations. Existing tanks can be internally insulated for liquid air storage. Liquid air is storable without pressurization. Oil and gasoline storage tanks can be converted to liquid air storage tanks. Liquid air can be stored in underground cavities,

Liquid air offers fast fill vs. the long waits associated with battery systems.

Liquid air controls require less cost, mass, and volume than electrical controls, including those required for automotive battery systems.

Liquid air storage vessels can be used as structural elements for mobile and stationary systems. Car, truck, train, plane, and ship structures can be made of tubes that can be used for liquid air storage. Truck and train chassis are very attractive candidates for tubular structures. Building structures can be formed from tubes used for cryogenic liquid storage.

Energy efficient buildings often suffer poor air quality as a consequence of reduced communication with the local atmosphere and liquid air can provide clean air in these applications. Clean makeup air can be especially valuable in hospitals. Operating rooms lamps can be designed to emit clean air to displace room air and operating team emissions in addition to liquid airs ability to provide cooling for the light sources and associated electronics.

Energy is proportional to pressure and liquid air at high pressure can have energy densities ~200Whr/kg, less than Li-Ion, but greater than Lithium Iron Phosphate, which Tesla and other EV mfrs. are transitioning to due to the reduced cost and increased safety. Electric vehicle batteries require costly heating, cooling, and control systems that further reduce their useful energy density. **Liquid air powered vehicles have reduced mass with travel, especially important with aircraft.**

Liquid air SuperHero atmospheric source heat engines can provide power densities 10-100 times as great as electric motors and without the concern of overheating.

In server farms Superhero liquid air turbogenerators can both power and cool the electronics. Electronics can operate at much higher power densities and with better efficiency, reliability, and durability via lower operating temperatures and modularity. Cryogenic cooling allows the use of lower bandgap semiconductors such as Germanium.

A liquid air economy will use liquid nitrogen and liquid oxygen. Liquid oxygens reactive potential makes it much more valuable than liquid nitrogen. Liquid oxygen can be used for combustion to greatly improve power density and to prevent oxides of nitrogen, it can be used for breathing, it can be used for high altitude operation, including rockets for point to point and space travel, and it is useful in many chemical processes. Liquid oxygen can be used for a SuperHero combustion engine topping cycle and liquid nitrogen can be used for a SuperHero cryogenic engine bottoming cycle.

## SuperHero Atmospheric Source Heat Engines

SuperHero Atmospheric Source Heat Engines can have high thermodynamic efficiency with cryogenic fluids. Additional benefits include safety, no need for ignition, no reaction time limits, no combustion space needed, drag heating utility, and boundary layer viscosity reduction via reduced temperature. See neweconomytechnology.com

Atmospheric source heat engines are limited by atmospheric air mass flow rate and this can be increased by increasing travel speed, a positive feedback loop.

## Bottom up Thermodynamics

Thermodynamic efficiency is limited by the absolute temperature ratio. Sadi Carnot gives us the thermal equivalent of height. If the temperature ratio is half, half of the thermal energy can be converted to work.

Maximum thermodynamic efficiency=1-$T_{low}$/$T_{high.}$ For liquid air $T_{low}$ @78$^0$K and ambient temperature $T_{high}$ @273$^0$K (1-78/273=0.71), or 71% maximum thermodynamic efficiency.

To achieve a similar thermodynamic efficiency with ambient temperature being $T_{low}$, $T_{high}$ must be ~900$^0$K (1-273/900=0.7). The higher operating temperature requires costlier materials and implies heat loss to the environment rather than heat gain from the environment as is the case with liquid air.

SuperHero turbomachines with cryogenic propellants can convert sensible heat from atmospheric air and latent heat from atmospheric water vapor to rotational motion which can be used for electricity generation, shaft work, or thrust.

Atmospheric energy conversion. Air specific heat @300K=1kJ/kg.K. A liquid air powered vehicle travelling at 120k/h (33m/s) provides ~40kg/s of atmospheric air to a 1m$^2$ aperture. 40kg/s X 100$^0$K $\Delta$T X1kJ/kg.K =4MJ/s or 4$Mw_t$. A portion of the thermal energy can be converted to rotational energy by SuperHero turbomachines and used to generate electricity, mechanical drive, or thrust.

Atmospheric energy conversion. Latent heat. Water liquid/gas latent heat of phase change energy =2.3kJ/gm. A vehicle travelling at 120k/h (33m/s) provides 33m$^3$/s of air to a 1m$^2$ aperture. Air at STP and 50% humidity contains 33m$^3$/s X 11.5 gms $H_2O$/m$^3$ X 2.3kJ/gm=873kJ/sec or 0.87$Mw_t$. 100%

humidity doubles this figure. Cryogenic SuperHero turbo machines can provide freshwater from the atmosphere via condensation.

SuperHero cryogenic turbomachines are attractive for working in hot areas, foundries, metalworking, ceramics, and glass industries. SuperHero cryogenic liquid nitrogen turbomachines are attractive for working in flammable and explosive environments.

### Cryogenic $CO_2$ Capture

SuperHero cryogenic turbomachines can benefit from the exhaust temperature from carbon containing fuel combustion and change the phase of $CO_2$ in the exhaust from a gas to a solid while delivering useful power. The $CO_2$ can be inertially separated at the source vs. trying to separate $CO_2$ from the atmosphere @400 parts per million.

LNG regasification facilities can be used to produce liquid air.

A thermos of liquid air and a small cryoturbine fan can provide a portable air conditioner without electricity.

Liquid air SuperHero turbomachines can power refrigerated delivery vans. Large numbers of refrigerated trucks spend their day in traffic with engine idling and with the refrigeration system operating to keep the food cold and with an air conditioner to cool the operator.

Liquid air can be used for projectile propulsion.

SuperHero cryogenic turbomachines can use heat from solar radiation, engine exhaust, industrial processes, and other sources to increase efficiency and power density.

### Epilog

Liquid Air Vehicles (LAVs) will displace EVs due to lower overall cost, including lower overall environmental cost. We will look back and say “You know there were people who thought that batteries would be cheaper than air”. Despite efficient manufacturing and direct selling, Tesla vehicles are expensive, and very heavy.

You can’t create batteries with photovoltaics, but you can create liquid air. PV can be used to create liquid air directly vs. batteries.

Batteries can’t be made from photovoltaic electricity, in fact Tesla does not even have his factory roofs covered with PV. Th mining and refining and manufacturing are costly.

The future is cool.

# SuperHero Microturbines

Why microturbines?

Power density is inversely proportional to length (1/L). Small turbines have the potential to reduce the cost, mass, and volume per unit power output and they are more amenable to mass production.

SuperHero technology encompasses a family of microturbines that include relatives of Hero's Aeolipile.

SuperHero technology allows high power/cost, high power/mass, and high power/volume microturbines. The family includes atmospheric source heat engines, internal and external combustion heat engines, topping and bottoming cycle heat engines, boiler feed pumps, immersive self-propelled, self-cooled, liquid rocket turbopumps, thrusters, fans, condensers, expanders, liquefiers, mixed flow compressors, motors, generators, power convertors. centrifugal blowers, open and closed cycle air conditioners, dehumidifiers, and reactors.

Superhero microturbines can provide power on a scale appropriate for homes, vehicles, and persons.

SuperHero microturbines can provide power as needed, when needed, where needed, and with the voltage/current ratio needed via modularity and without the long construction times associated with legacy power plants.

Superhero microturbines can provide reliability, maintainability, and throttleability by modularity.

Superhero microturbines can provide combined heat and power (CHP). ~60 million U.S. homes have natural gas supply. A SuperHero microturbogenerator with exhaust heat used for space heating and water heating can have >90% overall efficiency, provide reliable low-cost electricity and reduce grid dependence. Natural gas is less costly than electricity and less subject to outage.

SuperHero microturbogenerators are attractive for uninterruptible power supplies and emergency power production.

SuperHero backpack microturbogenerators can provide electricity and compressed air for construction and landscaping tools. SuperHero microturbine driven machine tools can provide high power density and cooling.

Why haven't microturbines been more successful, despite the potential benefits?

Large turbomachines dominate in commercial air transport and electricity generation, but when the size of legacy turbomachines is reduced, some of the beneficial characteristics are reduced, often to a degree that render them unable to compete with other means.

**Cost:** the cost of legacy turbomachines is due in large part to the manufacturing processes associated with complex blading and the cost of materials able to operate with high thermal and mechanical loads. SuperHero microturbines incorporate manufacturing simplicity and commodity materials.

**Efficiency:** efficiency is proportional to $L^{2/3}$ (square/cube law), but the loss mechanisms associated with scale reduction in turbomachines are mitigated in SuperHero microturbines by using enclosed passages to avoid rotor to stator leakage, by the use of liquid working fluids, and by advantageous heat exchange with the environment associated with increased surface/volume, especially with cryogenic fluids.

SuperHero microturbines use rotating tube arrays as compressors or blowers and the rotor drag can also be useful thermodynamically, especially in the case of cryogenic liquid propellants.

**Shear force:** the reduction in passage size associated with scale reduction in microturbines implies increased shear force per unit fluid flow (<Re) and this increase in the ratio of shear to inertial force is associated with increased drag. The relative shear force increase may be inevitable, but not inevitably bad. Small passages allow increased heat transport rates and SuperHero microturbines can be designed to operate with laminar flow where drag is proportional to velocity rather than the square of velocity associated with turbulent flow. Laminar flows also produce less noise.

A classic argument against tip jets is that efficient operation requires unrealistic tip speeds.

SuperHero microturbines combine modern materials and proprietary design to allow much higher tip speeds than legacy reaction turbines and the technology provides several means to use the energy downstream of the jets, including rockets, concentric contrarotating radial outflow impulse turbines, contrarotating tipjet rotors, entrainment, volutes, blown wings, and deswirl vane arrays.

**Fig.1 SuperHero Tipjet Reaction Microturbine**

The radial tubes in the arrays of Fig.1 are composed of 1.5mm OD X 0.1mm wall thickness (17Ga) 304 stainless steel hypodermic tubing. Superhero microturbines can generate higher pressures in a single stage than multistage legacy microturbines by using liquid propellants.

The rotating tube arrays in SuperHero microturbines cause fluids introduced through a central hollow axle to be accelerated in the tubes and ejected tangentially at the tube ends or returned to the hollow axle via "U" tubes.

The tube arrays can be configured as centrifugal, axial, or mixed flow compressors and blowers.

SuperHero microturbines are rotating high power density heat exchangers capable of extremely high pressures i.e., thousands of atmospheres. The extreme pressures are confined to small regions which also serve as high-rate heat exchangers. Torque can be additive and/or subtractive.

A large population of small jets allows increased coupling with the neighboring airstream for mass, momentum, and heat transfer. Jet expansion causes a reduction in temperature that can be mitigated by close association with the neighboring airstream. The neighboring airstream may be at atmospheric temperature or preheated.

SuperHero microturbines can have many rotating tube arrays and bilateral entry.

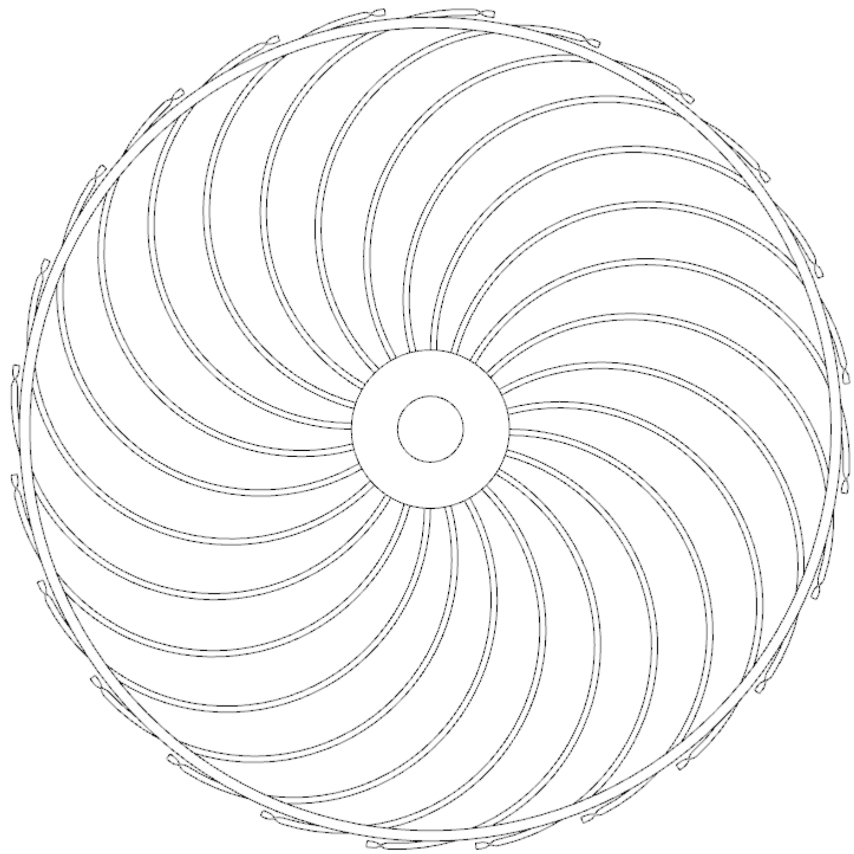

Fig. 2 SuperHero Tipjet Reaction Turbine with Backswept Passages

Fig. 2 is a SuperHero centrifugal microturbine rotor comprising a backswept stainless steel hypodermic tube array with C-D nozzles via plastic deformation and with brazed 4GPa tire cord wire supporting rings. Backswept tubes reduce drag and increase fill factor

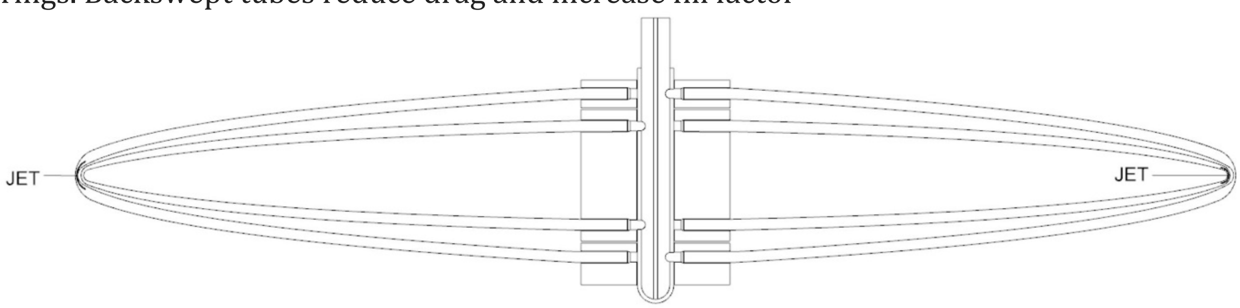


**Fig.3 Contrarotating Parabolic Tube Array Schematic**

Fig.3 is a pair of contrarotating radial reaction turbine arrays that can provide intense mixing and add torque to opposing turbine array. The jets from one rotor encounter opposing high velocity flows from neighboring rotors. The contrarotation can provide intense mixing, reacting, and combustion.

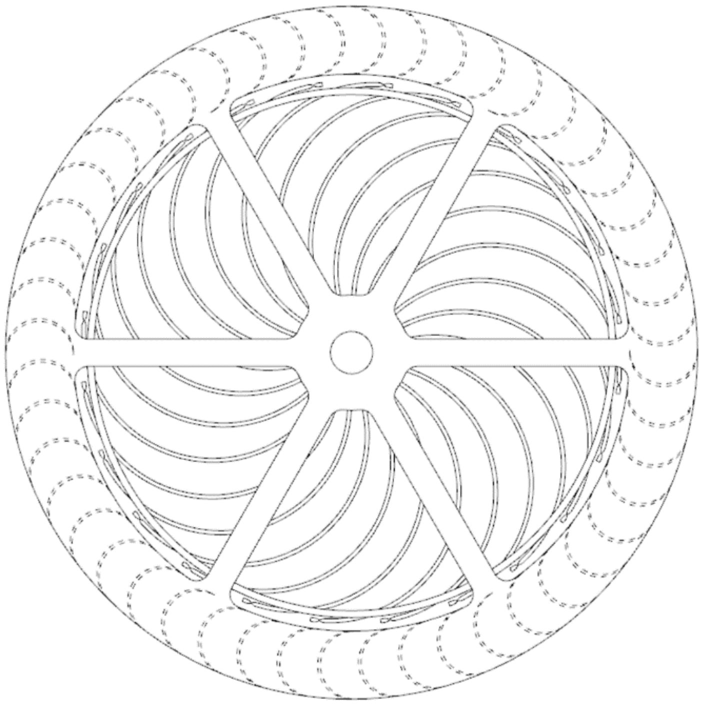

Fig. 4 SuperHero Tipjet Reaction Turbine with External Impulse Contrarotor

In Fig. 4 the SuperHero inner reaction turbine output drives a concentric contrarotating impulse turbine and the large number of nozzles provides high power density. One or more concentric contrarotating impulse turbine stages can be used in radially outflowing SuperHero microturbine systems to provide output power with increased efficiency, lower output rotational rate for connection to drives, reduced exhaust temperature, and reduced exhaust velocity.

Contrarotor spokes can be increased in number and used to induce air.

SuperHero microturbines can provide net positive suction head for pumping unpressurized propellants.

The incoming fluid passage between static axle and rotor can provide a hydrostatic journal bearing.

A rotor with 0.1m radial length liquid phase rotating at 45krpm will develop a centrifugal pressure equal to ($1/2\rho r^2\omega^2$). A liquid air density $\rho$=870kg/m$^3$ X 0.5 X 0.1m$^2$ X $\omega$4,710$^2$=9.65 X10$^7$N/m$^2$ or 965atm with an angular velocity of 471m/s.

17 Gauge thinwall 304 SS hypodermic tubing has an OD of 1.5mm, a wall thickness of 0.1mm, and a tensile yield strength of 944MPa. The hoop stress at 1,000 atmospheres (s=pr/t) is 650MPa, which yields a safety factor of ~1.5 at 1,000atm, and the high pressure is confined to a small region, allowing low wall mass and cost. 2GPa 301 stainless steel allows 2X pressure increase and 4GPa wire braided sleeve and helical bottlebrush inserts allows much greater pressure increase.

Low temperature and cryogenic SuperHero microturbines benefit from increased material strength at low temperature and the ability to use advanced nonmetallics such as carbon fiber and graphene.

A helical “Bottlebrush” internal structure can be used to provide an array of ties normal to the tube axis to resist outward pressure forces and provide extended surface area for heat exchange. The bottlebrush can use 4GPa wires and attach to the tube ID by brazing. Adding a helical moment counters the Coriolis force causing flow to follow the trailing edge of the tube wall and prevents Dean vortices due to tube curvature. 4GPa central twisted wire can provide increased axial tensile strength. The bottlebrush can be catalyzed to react with fluids in passage for combustion or operation as a chemical process reactor.

The thinwall tubes and high rotation rates in SuperHero microturbines provide high heat transfer rates, but extended surfaces can be used to greatly increase heat transfer rates. Commercially available 635 mesh (635 wires/inch in each of 2 axes)=(250 wires/cm in each of 2 axes) stainless steel twill weave wire cloth with 18um wire can be used to create a very high heat transfer rate rotating heat exchanger/engine.

The wire cloth elements can be bias cut at $45^0$ to equalize heat transfer for wires in both axes and to reduce edge affects. The wire cloth elements can be anchored at the hub and brazed to the tube arrays.

Custom wire arrays can use high strength steel wires with copper cladding for increased heat transfer and brazing. The wire arrays can be brazed to the trailing edge of the tubes, making the tube arrays part of a hierarchal flow organization.

The rotating wire cloth arrays are somewhat analogous to crossflow filtration schemes. The high surface velocity parallel to the wire cloth arrays and the pressure difference across the wire cloth arrays provide very high heat transfer rates. The system can be designed for air to make a single pass through the capillary mesh.

SuperHero hierarchal microscale heat exchanger power density is due to the high surface/volume ratio associated with the fine wire mesh, the related thin boundary layers, massive end stage parallelism, and laminar flow.

Ref.1 details free convection heat transfer from small features. Pulavarthy Thesis “CHARACTERIZATION OF HEAT TRANSFER COEFFICIENT AT MICRO/NANO SCALE AND THE EFFECT OF HEATED ZONE SIZE”. “The measured heat transfer coefficient varied from 4650 $W/m^2K$ in a 10 μm X 20 μm freestanding specimen to 16,300 $W/m^2K$ for the same specimen 2 μm away from a neighboring solid surface”. “It is to be noted that the results discussed in this section are for the experiment carried out at atmospheric pressure”.

SuperHero microturbines are the property of John Popovich and have patent pending status.
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