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THERMAL MANAGEMENT IN HEAVY VEHICLES: A REVIEW IDENTIFYING ISSUES AND RESEARCH REQUIREMENTS*

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ABSTRACT

Thermal management in heavy vehicles is cross-cutting because it directly or indirectly affects engine performance, fuel economy, safety and reliability, engine/component life, driver comfort, materials selection, emissions, maintenance, and aerodynamics. It follows that thermal management is critical to the design of large (class 6-8) trucks, especially in optimizing for energy efficiency and emissions reduction. Heat rejection requirements are expected to increase, and it is industry's goal to develop new, innovative, high-performance cooling systems that occupy less space and are lightweight and cost-competitive. The state of the art in heavy vehicle thermal management is reviewed, and issues and research areas are identified.

KEYWORDS: Thermal management, heat exchangers, fans, pumps, heat transfer, trucks.

1 INTRODUCTION

With the trend toward more powerful engines (up to 600 hp), more air conditioning, more stringent emissions requirements, and additional auxiliary equipment, the heat rejection requirements of large trucks can be expected to grow substantially (an estimated 40-60%) in the near future. In addition, engine performance requirements are expected to increase, along with demands for longer component life, reduced maintenance, and improved driver comfort and safety. The challenge will be to design higher-performing thermal management systems that occupy less space, are lightweight, and have reduced fluid inventory.

Unlike the automotive industry, where a particular vehicle model is mass-produced, large (class 6-8) trucks are typically custom-designed. In fact, successive trucks leaving an assembly line typically will have different engines and different cooling system requirements, making design and optimization of truck thermal management systems even more difficult. Engine manufacturers, truck manufacturers, and equipment suppliers each have a role to play.

This paper summarizes a study funded by the U.S. Department of Energy, Office of Transportation Technologies, Office of Heavy Vehicle Technologies. The objectives of the study were to (a) review the state of the art and trends in truck thermal management; (b) identify opportunities for improving thermal management systems to realize overall benefits such as improved fuel economy, reduced emissions, reduced weight, improved aerodynamics, and reduced fluid inventory; and (c) identify new technology and research that can effect such improvements. Information and background material gathered from an open literature review was integrated with and supplemented by information obtained during site visits to manufacturers of trucks, engines, and equipment to provide the basis for a report that is summarized in this review paper.

2 STATE OF THE ART/ISSUES

A truck thermal management system comprises an assembly of heat exchangers, fan(s), pumps, compressor(s), sensors, actuators, shrouds, piping or hoses, and various heat transfer fluids. This assembly of fluids and components must work together to satisfy the specific system requirements. The performance of the system is not simply related to performance of individual components, but is determined in large part by how these components interact during on-highway operation of the vehicle.

In the following, the various elements/components comprising a truck thermal management system are considered individually.

2.1 Heat Transfer Fluids

The heat transfer fluids in a vehicle thermal management system include ambient air, coolant, intake air, engine oil, transmission oil, fuel, exhaust gas, and refrigerant(s). A flow circuit can be associated with each fluid. The heat transfer to or from these fluids will be determined by the fluid's transport properties, mass flow rate, and the temperature difference between the fluid and heat transfer surface. All of these fluids exhibit poor heat transfer because of their relatively low thermal conductivity and specific heat. As a result, enhanced surfaces and methods to improve a fluid's heat transfer characteristics take on added importance. In some cases, e.g., fuel, there is a need to better understand and characterize thermal properties.

2.2 Heat Exchangers

Heat exchangers are the heart of a vehicle thermal management system. For a typical truck thermal management system, these heat exchangers include the radiator, charge-air cooler (intercooler), oil coolers, fuel cooler, air conditioning (A/C) evaporator and condenser, devices for cooling electronics, exhaust gas recirculation (EGR) coolers, and, as applicable, refrigeration system evaporator and condenser.

Design criteria applicable to all such heat exchangers are high performance (high thermal effectiveness and high heat transfer per unit of pressure drop), light weight, small size (compactness), reduced fluid inventory, mechanical strength, high reliability/durability, low cost, and minimal environmental impact during both production and eventual disposal/recycling.

Reducing the size of the heat exchangers will generally reduce weight and allow for improved aerodynamics, both leading to improved fuel economy. Modifying the shape of certain heat exchangers also has the potential to improve aerodynamics. Smaller size means a reduced fluid inventory and thereby decreased cost of the working fluid charge, while simultaneously reducing the environmental impact associated with the production of the fluid and eventual disposal. A more compact unit with reduced fluid inventory means a faster response to changes in operating conditions. Enhanced surfaces are widely used because, as noted above, the fluids used are inherently poor heat transfer fluids. Cost is important, because new and innovative designs must be cost-competitive if truck manufacturers are to use them.

2.3 Fan System

The fan system provides air flow to the air-cooled heat exchangers to achieve the required heat transfer at idle and low speeds, that is, when ram air is not available. At high speeds, ram air is usually sufficient and the fan will shut off; fan control is automatic, but can often be overridden by the operator. The fan must overcome pressure drops due to the air inlet at the front of the vehicle, airflow through the heat exchangers, and airflow over the engine block and related components.

Fan power requirements in large trucks can be 35 to 50 kW. This high energy draw highlights the effect of the fan system on fuel economy. With such large power requirements, electric drives are impractical. Therefore, axial fans, directly driven by the engine, are used. A fan shroud optimizes airflow through the radiator, while a viscous clutch and a thermostat control fan operation.

Fan efficiency, size, noise, and vibration are all important issues. There is a need for high-efficiency motors, viscous clutches, and variable-speed drives. Research is required on all fan types: axial, direct engine-driven, electrically driven, and radial.

2.4 Pumps

Pumps circulate the coolant and oil to the engine and through the appropriate heat exchangers. These pumps require energy from the engine and thereby affect fuel economy. In large trucks, the coolant pumps are engine-driven through a pulley or gear arrangement. As a consequence, pump speed is directly related to engine rpm. However, cooling requirements typically are not directly related to engine rpm, but depend on numerous other parameters. It is therefore possible to overcool the engine, with a concurrent negative effect on fuel economy and emissions. There is a need for variable-speed drives and also for high-efficiency electric motors. Availability of an electrically driven coolant pump would enable control of pump speed and the ability to locate the pump optimally in the engine compartment.

2.5 Underhood Airflow

Underhood airflow is the ultimate heat sink for all rejected heat. The performance of a truck's engine cooling and A/C systems is directly related to the management of airflow through the engine compartment. The underhood airflow is determined by the truck design (styling and underhood compartment), fan system, engine size and design, cooling system components, vehicle speed, and ambient air velocity. Its distribution is extremely complex. The airflow is provided by the fan system at idle and low vehicle speeds, and by ram air at high vehicle speeds. Aerodynamic styling typically results in less available grille area and underhood space. This tends to increase the heat load because of restricted airflow and gives rise to a greater airflow pressure drop. Restricted airflow can contribute to an overheated underhood environment, which can contribute to component malfunction and premature failure of materials and components. An increase in pressure drop puts an added load on the fan system. To improve performance, the airflow must be "managed."

2.6 Aerodynamics

Aerodynamic drag has a significant detrimental effect on fuel economy because a significant fraction of a vehicle's total available power is used to overcome it. Drag reduction efforts have focused primarily on external air flow—over and around the tractor-trailer combination—and its effect on drag coefficient. In current tractor-trailer designs, the contribution to overall vehicle drag from underhood flow is considered small relative to that from external flow (1). However, as the external flow contribution to overall drag coefficient is reduced, the contribution from underhood airflow as a fraction of the total aerodynamic drag can be expected to increase. As a consequence, reducing the contribution from underhood airflow can significantly reduce drag, with concurrent energy savings. The contribution of underhood airflow to aerodynamic drag, lift, and side forces has been shown to be significant for automobiles (2), influencing driving performance, vehicle stability, and fuel economy. The importance of these forces for large trucks remains to be determined.

2.7 Brake Cooling

Most large-truck brakes use finned drums, relying on airflow to transport the heat away. However, as vehicle aerodynamics are improved, and drag forces are reduced, demands on the braking systems increase with concurrent increases in braking heat dissipation requirements. To supplement downhill braking, engine braking is often used. Operators will also manually engage the fan to obtain retarding. Both strategies increase the heat rejection requirements, putting an additional load on the radiator. Techniques to improve brake cooling will be needed.

2.8 Modeling and Simulation Studies

Unlike the automobile industry, in which a particular model is mass-produced and the cooling system can be "fine-tuned" and optimized, large trucks are typically custom-designed. Therefore, it is more difficult to optimize a truck thermal management system, because each truck can have somewhat different cooling requirements.

Recent practice has been to select—based on experience and in-house design procedures—the various components of a thermal management system, assemble and install the components in a truck, and then test the truck at rated load and speed to determine if the cooling system meets the engine manufacturer's requirements. If the requirements are not met, the components are changed and the tests are rerun. Such testing is both time-consuming and expensive. To avoid these costs and to achieve a more optimal cooling system design, designers and analysts are turning to computer simulation codes. In addition to steady-state design, such codes have the added advantage of simulating the effects of transient conditions such as hill climbing or downhill braking, when heat rejection rates can be the highest. Numerical simulation has the obvious advantage that it allows screening a number of designs without time-consuming and expensive experimental wind tunnel studies. Computational fluid dynamics also allows thermal management requirements relative to styling and front-end design to be included early in the vehicle design. The accuracy of much of the modeling is questionable unless test data from heat transfer equipment are used.

VECSS (Vehicle Engine Cooling System Simulation) is a truck cooling system simulation tool under development at Michigan Technological University since 1982 (3). The program runs on a PC and includes numerical modules representing all of the major components: engine, turbocharger, radiator, charge air cooler, fan, thermal control devices, coolant and oil flow circuits, and air conditioner. The component models were developed from experimental data. Field test data were obtained from a Freightliner truck with a Detroit Diesel engine. Agreement between predicted and measured temperatures has been excellent.

There is abundant open literature on numerical simulation of cooling system components and the cooling system itself. The vast majority of the papers address automotive applications. The trucking industry recognizes the need for such a capability and is beginning to develop it.

2.9 Sensors and Actuators

Sensors for temperature, pressure, engine speed, flowrates, and airflow velocity are available commercially, and today's modern trucks are highly instrumented. New sensor development in the marketplace is ongoing and can be expected to provide even more miniaturization, robustness, and accuracy.

Actuators include thermostats, shutterstats, temperature- and pressure-activated control valves, and variable-speed drives. Many of these are commercially available. For example, shutters are available with air cylinders for opening and closing. However, there is a continuing need for improvements and new and innovative products.

2.10 Materials and Fabrication

Materials and fabrication techniques play an important role in vehicle thermal management; Gupta (4) reviewed the materials impact on automotive thermal management. Lighter-weight materials (for example, aluminum, plastics, and carbon composites) would reduce weight and cost. However, temperature and the ability to cool directly affects the selection of materials that can be used in engines and related components, such as catalytic converters. Temperature affects material properties and ultimately the strength and reliability of a component. Many lightweight materials are temperature-limited. There is an interest in plastics, for weight and cost savings, and formability. However, long-term durability, aging, and compatibility with heat transfer fluids are concerns. Cost is a limiting factor for materials such as carbon composites.

Select heat exchangers must be designed to increasingly more severe conditions. Charge-air coolers, with air temperatures exceeding 220°C (5), and exhaust gas recirculation coolers, with exhaust gas temperatures in the range 500 to 600°C, are two examples.

2.11 Reliability/Safety/Environment

Reliability is of highest importance—if the truck's cooling system fails, the truck can not operate. In general, a cooling package has an expected lifetime of 750,000 miles, with a 100,000 mile maintenance cycle. Such requirements for high reliability can be considered a barrier to the implementation of any radical and innovative ideas and designs for vehicle thermal management systems; any new ideas/designs must first be proven reliable.

With regard to safety and minimization of injury to drivers and passengers in the event of an accident, energy- or shock-absorbing materials/devices incorporated in truck front ends would be beneficial. This would require moving the radiator to a remote location, or designing shock-absorbing capabilities into the grille/radiator/support structures.

With regard to environmental and health concerns, ingestion of ethylene glycol (currently used as a coolant in most vehicles) by humans or animals is known to be harmful or fatal and alternative coolants are being developed. The ability to recycle/reprocess used coolant is also increasing in importance, as is global warming potential for refrigerants. "Natural refrigerants" such as air, water, ammonia, hydrocarbons, and carbon dioxides are being considered as possible solutions to the problem of finding environmentally acceptable refrigerants for air conditioning and refrigeration applications; most attention is being given to CO_2 (6).

3 NEW/INNOVATIVE CONCEPTS

In the following, several new and innovative concepts are discussed. Some have been proposed for, and are already being used in, automotive applications. In general, research will be required to further the development of these concepts, and extensive testing, including field testing, will be required to establish reliability and maintainability. The latter are crucial for ultimate acceptance by the trucking industry.

3.1 Compact Cooling System Based on Radial Fan

A new cooling system concept, termed the compact cooling system (CCS), has been proposed (7). In contrast to a conventional cooling system, which is an "axial system" in the sense that an engine-driven axial fan draws air through heat exchangers that are stacked in-line or arranged side-by-side, the CCS is a "radial system." It is based on a radial fan, with the heat exchangers (radiator, CAC, and condenser) positioned around the fan. There are several advantages with this type of system: (a) each heat exchanger sees the coolest ambient air (i.e., all airside surfaces work at ambient temperature); (b) independent control of the airflow through each heat exchanger with shutters is easy; (c) the fan is in front of heat exchangers, working with the coolest, highest-density air to give a higher mass flow velocity; (d) the radial fan can be engine-mounted in the traditional manner; (e) fan power requirements are reduced; and (f) a radial fan is less noisy. Ability to control all cooling components independently is an important benefit; for example, the CAC is not required during braking and can be "shuttered off" to allow more airflow through the radiators without having to increase fan speed. An inherent disadvantage of the CCS is that "packaging" may be a problem because of limited "fore-to-aft" space in the engine compartment.

Substantial development work is required to develop a radial fan and fan drive, engineer the interfaces of fan/cooling-system-components/engine, and integrate the total assembly into a truck.

3.2 Computer-Controlled Systems

Thermal management, when taken literally, means an optimally designed cooling system with demand-responsive control and supply of mass and heat flows to maintain critical engine and engine-related component temperatures within acceptable ranges (8). Such a computer-controlled thermal management system requires sensors, actuators, microprocessors, and control algorithms. Sensors, most of which are already available, are required to measure such parameters as temperature, pressure, and flowrates at critical points in the engine and in the air and coolant circuits. The operating conditions of the engine (speed and torque), fan and pump speeds, and ambient temperature must also be measured. Actuators are required to control air and coolant flows. The actuators would include controllable fans, pumps, valves, flaps, restrictors, and baffles; some of these are available, while others would have to be developed.

The measured parameters, together with input signals from other components, e.g., brakes, and/or operator commands, would be input to a microprocessor-based control system. The cooling system actuators would be controlled according to prescribed control objectives. Computer-controlled thermal management systems will lead to optimal engine performance and an associated reduction in fuel consumption and pollutant emissions, will shorten the cold-start phase, and will reduce thermal stresses on components. Among other things, it should be possible to tie a computerized system to a global positioning system (GPS) to anticipate steep grades and increased heat loads. Researchers at Michigan Technological University have proposed a computer-controlled truck thermal management system that would save energy and improve energy management (9).

3.3 Hybrid Convective/Nucleate-Boiling Heat Transfer

While virtually all internal combustion engines are designed to be cooled by forced convection, nucleate boiling remains the most efficient form of heat transfer. The onset of nucleate boiling dramatically increases the amount of heat transferred to the fluid, resulting in a lower wall temperature. In nucleate-boiling cooling, the coolant is vaporized in the engine, absorbing the engine heat, and condensed in the radiator. The advantages of this mode of heat transfer are (a) very high heat transfer coefficients; (b) lower coolant mass flow rates; (c) smaller, less-expensive hoses; (d) smaller fluid inventory; (e) smaller water pump, requiring less power; (f) fuel savings; (g) uniform temperature distribution, readily controlled by controlling system pressure; and (h) with the option of a relatively small electric coolant pump replacing the larger engine-driven pump, more freedom in selecting the pump location. System pressure is important in controlling this heat transfer mode. Expansion of the coolant vapor must be accommodated with an expansion tank. Film boiling and dry-out must be controlled and prevented to avoid dangerous hotspots and overheating as a result of the poor heat transfer coefficient.

A hybrid forced-convection/nucleate-boiling system, in which convective heat transfer would handle perhaps 95% of the cooling requirements and nucleate boiling would handle the remaining 5% associated with thermally severe conditions, would remove much of the conservatism built in to current truck thermal management systems and can be expected to lead to smaller heat exchangers, fans, and pumps, with a concurrent reduction in energy draw to power the fan and pump drives. Ap and Golm (10) and Porot et al. (11) have proposed such a hybrid system. Coolant inlet temperature and system pressure strongly influence evaporative cooling and can be used to control the range of flow rate corresponding to stable, evaporative cooling. The geometry and size of the coolant flow passages in the cylinder head will be important design parameters requiring investigation.

3.4 Advanced Heat Transfer Fluids

There is a general need to improve the heat transfer characteristics of fluids used in vehicle thermal management systems. An emerging technology that shows promise is that of nanofluids (12,13). Nanofluids are a class of engineered heat transfer fluids formed by dispersing nanometer-sized metallic particles in traditional heat transfer fluids such as water/ethylene glycol mixtures and oils to improve thermal conductivity. Test results (13) have shown that increases of up to 40% in thermal conductivity are possible for water/ethylene-glycol solutions; the results are a function of the nanoparticle material and the volume percent of nanoparticle loading. A recent paper (14) illustrates how nanoparticles introduced into oils can improve their lubricity and load-carrying capacity. Thus it may be possible to achieve multiple benefits from application of this technology.

3.5 Heat Transfer Enhancements

Passive heat transfer enhancement methods, including louvered finning for use on the gas (air) side, and dimpled surfaces for use on the liquid side, have been extensively studied and developed, and it is not likely that more than incremental improvements can be realized. Innovative enhanced surfaces with acceptable pressure drops are needed that can function satisfactorily throughout the laminar, transition, and turbulent flow regimes, as certain heat exchangers encounter all of these flow regimes during operation. Electrohydrodynamic (EHD) enhancement is an example of an active enhancement. Smart materials, which respond to external stimuli such as temperature and pressure, may have application in the development of enhancement devices, optimized for flow regime and pressure drop.

3.6 Waste Heat Recovery

The distribution of energy available in the fuel varies widely, depending on engine design and load. However, it is reasonable to assume that the energy is distributed approximately 1/3 to motive power, 1/3 to the exhaust, and 1/3 to the coolant. As a consequence, significant waste heat is available to be recovered to drive an electric generator or to provide power to the crankshaft. This waste heat is also available to be stored, for example, in a heat battery. Recovery and use of waste heat can reduce fuel consumption and emissions.

Various waste heat recovery and utilization schemes have been proposed. The following are examples: Keller et al. (15) proposed a thermal storage heating and A/C system that is charged from the vehicle's engine coolant or air conditioning system, and tested the system on a Navistar cabover model truck and on a Freightliner hi-rise conventional truck; Zobel and Strähle (16) proposed a latent-heat storage battery that collects and stores engine waste heat to enhance the efficiency of the vehicle's heating, reduce engine warm-up time, improve emissions warm-up performance, reduce fuel consumption, and provide instant interior heating and windshield defrosting; Mostafavi and Agnew (17,18) proposed the use of exhaust gases as an energy source in an absorption refrigeration unit to provide cooling for the CAC; de Beijer and Klein Horsman (19) proposed a thermochemical heat pump (an absorption system using a hydroscopic salt, Na_2S) that can be charged with waste heat taken from the coolant or from exhaust gases; and a Rankine cycle was proposed by Hay and Hay (20) to recover the energy available in the cooling water to produce electric power or to contribute to the motive power.

Heat recovery can also be used for endothermic fuel reforming reactions in which exhaust gas thermal energy is transformed into reformed fuel chemical energy, implying improvements in overall engine efficiency; exhaust gas temperatures exceeding 700 to 750°C at the reactor inlet are required to promote the endothermic reactions. Jones and Wyszynski (21) presented the design, construction, and testing of a reforming reactor. Heat recovery might also be used in thermal-electric converters to power fuel-reforming devices such as the plasmatron (22).

4 RESEARCH REQUIREMENTS

Table 1 summarizes the research that is required to enable the development and design of high-performance heavy vehicle thermal management systems that are innovative; smaller; lighter-weight; reduce energy draw; and improve fuel economy, maintenance, and reliability. Benefits to be derived from such research are also included. The items in Table 1 follow the discussion items in Sections 2 and 3 of this review, and are so referenced.

Table 1 Research Areas and Benefits

ITEM	RESEARCH OBJECTIVES	RESEARCH AREAS	BENEFITS
Heat Transfer Fluids (2.1, 3.4)	Improve heat transfer Reduce pressure drop	Additives – nanofluids Heat transfer characterization New coolants Natural refrigerants	Compact designs Reduced fluid inventory Fuel economy Environmentally acceptable fluids
Heat Exchangers (2.2, 3.1)	Compactness – microscale Lightweight High efficiency Shaped heat exchangers	Enhanced surfaces – laminar/transition/ turbulent regimes Active enhancements Flow maldistribution Materials Fabrication techniques	Fuel economy Increased payload Improved aerodynamics Improved maintenance Improved reliability
Fan System (2.3, 3.1)	Variable speed High efficiency Lightweight Noise Vibration	Materials Bearings Drives Fan blade designs Radial fan design Flow distribution	Reduced energy draw Reduced noise Reduced vibration Improved maintenance Improved reliability Fuel economy
Pumps (2.4)	Variable speed High efficiency Lightweight	Materials Bearings Drives Impeller designs	Reduced energy draw Improved maintenance Improved reliability Fuel economy
Underhood Airflow (2.5)	Manage airflow	Shrouds Seals Air intake (grille) Air exhaust Fan/ram air	Reduced pressure drop Reduced energy draw Improved aerodynamics Improved heat exchanger performance
Aerodynamics (2.6)	Reduce drag	More compact heat exchangers Effect of air intake/exit	Fuel economy
Brake Cooling (2.7)	Improve cooling	Materials Cooling technology	Safety Improved maintenance

Modeling and Simulation (2.8)	Validated simulation tools – individual equipment – system PC-based codes	Prediction methods Correlations Code development Validation data – components – system	Facilitate design Reduce testing time Design cost-savings Basis for computer-controlled system
Sensors & Actuators (2.9)	Miniaturization Robustness Accuracy	Application of new technologies	On-line monitoring Enable computer control
Materials & Fabrication (2.10)	Lightweight Strength Durability Low cost	Application of new technologies Smart materials Composites Plastics – nanoparticle-loaded	Fuel economy Improved maintenance Improved reliability
Computer-Controlled Systems (3.2)	Develop methodology for computer control	Control algorithms Application of sensors and actuators	Controlled cooling Fuel economy Engine performance Emissions reduction
Hybrid Convective/ Nucleate Boiling Heat Transfer (3.3)	High heat transfer coefficients Lower mass flow rates Uniform temperature	Effect of channel size and geometry Critical heat flux (CHF) Control of CHF Correlations	Fuel economy Precision cooling Lower thermal stresses Reduced fluid inventory Smaller coolant pump Smaller hoses
Waste Heat Recovery (3.6)	Develop waste heat recovery technologies	Application of heat recovery technologies – absorption cycle – Rankine cycle Heat exchanger/reactor design	Thermal storage Supplemental cooling and heating Fuel economy Fuel reforming Reduced emissions

5 CONCLUDING REMARKS

Over the past several decades, improvements in vehicle thermal management systems and subsystems have generally been evolutionary rather than revolutionary as cooling requirements increased, new materials and fabrication methods became available, and new heat transfer fluids were developed or mandated. With evolutionary development, improvements have typically been incremental, based on trial-and-error, and guided by engineering experience and judgment. To effectively meet the requirements for additional cooling, as well as controlled cooling, brought on by the trend to higher-horsepower engines; stringent emissions requirements; and fuel-efficiency, reliability, safety, and environmental mandates, there is now a need for radical and innovative improvements. The important issues relative to the development of improved thermal management systems for large trucks have been reviewed here, and various new and innovative technologies and designs to improve these systems have been highlighted, together with the related research requirements.

The aircraft, aerospace, and electronics industries have many of the same thermal management requirements as heavy vehicles and automobiles, i.e., cooling systems that require high performance, small size, low weight, and reduced fluid inventory. Much may possibly be gained from a review of these thermal management systems and adopting those features that would be beneficial in truck thermal management. Among other things, this would include reviews of materials and fabrication techniques, as well as heat transfer surface enhancement techniques.

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