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Aerodynamic Drag and Drag Reduction: Energy and Energy Savings (Invited)

Richard M. Wood
NASA Langley Research Center
Hampton, Virginia

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ABSTRACT

An assessment of the role of fluid dynamic resistance and/or aerodynamic drag and the relationship to energy use in the United States is presented. Existing data indicates that up to 25% of the total energy consumed in the United States is used to overcome aerodynamic drag, 27% of the total energy used in the United States is consumed by transportation systems, and 60% of the transportation energy or 16% of the total energy consumed in the United States is used to overcome aerodynamic drag in transportation systems. Drag reduction goals of 50% are proposed and discussed which if realized would produce a 7.85% total energy savings. This energy savings correlates to a yearly cost savings in the $30Billion dollar range.

INTRODUCTION

There are a number of fundamental forces in nature that influence our way of life, three of these forces are; gravity, fluid-dynamics (i.e. wind and water forces) and solid mechanics (i.e. earthquakes). It is argued that after gravity, fluid-dynamics is nature's most prevalent force on earth. We spend our life interacting with a variety of fluids from the air we breath and water we drink to the storms we shelter from. Fluid-dynamic forces have a significant influence on transportation, recreation and sport. A review of data from the Department of Energy (DOE) indicate that there are numerous fluid interactions that influence the energy consumption of our transportation systems, manufacturing processes and heating and cooling needs. [1-3].

To assess the relative magnitude and impact of these forces on our life a review of the energy consumption associated with the wide array of processes and systems that involve fluid interactions. At first review it is clear that an assessment of the complete role of fluid-dynamics in our life is not only extremely complex but it is beyond the scope of a single paper. To reduce the scope of this topic the following discussion will be limited to fluid dynamic resistance and/or aerodynamic drag and the relationship of drag to energy use in the United States.

To help clarify the focus of this discussion the following definition of fluid-dynamic resistance is offered to the reader. Fluid-dynamic resistance is defined as the force resulting from the interaction of a fluid with a solid object that opposes the desired motion of the fluid or solid object. It is important to note that the term fluid-dynamic resistance will be used interchangeably with aerodynamic drag. The purpose of relating the discussion to aerodynamics is simply a refection of the author's area of expertise. Note, the energy used to overcome gravity will not be discussed.

A review of the literature show that previous discussions of aerodynamic drag have been either discipline focused [4, 5] such as aircraft or ground vehicles; in order to accentuate the unique character and features of a research area or they have been narrower in scope by focusing on a single vehicle class such as a transport or a fighter aircraft. This discussion, while focusing on aerodynamic drag, will not limit the discussion to aircraft drag reduction, but will review the general topic of fluid-dynamic resistance and/or aerodynamic drag and relate these observations to energy consumption. The discussion of energy consumption provides a direct connection to the economic impact of the technologies that are capable of reducing aerodynamic drag and it provides a technical connection to other disciplines and industries that benefit from aerodynamic drag reduction technologies.

The relationship between aerodynamic drag and energy use in the United States (US) can be obtained by reviewing data from the Department of Transportation (DOT) and the DOE[1-3, 6-11]. An analysis of the DOE and DOT energy data coupled with a fundamental understanding of the role of fluid-dynamic resistance on transportation, manufacturing and heating/cooling requirements allows for the following estimates of energy use in the United States (U.S.). Note, the listed estimates will be discussed further in the following section of the paper.

- 25% of the total energy consumed in the United States is used to overcome aerodynamic drag.
- 27% of the total energy used in the United States is consumed by transportation systems
- 60% of the transportation energy or 16% of the total energy consumed in the United States is used to overcome aerodynamic drag in transportation systems.

These estimates indicate that, in addition to transportation, the Industry and Residential/ Commercial areas consume an additional 9% of the total energy used in the United States at overcome aerodynamic drag (fluid-dynamic resistance). This observation highlights the importance of including non-transportation industries and technologies in the discussion of aerodynamic drag.

All transportation systems and manufacturing processes involve either the movement of solid structures through fluids or the movement of fluids past solid structures (i.e. aerodynamics, hydrodynamics and fluid-dynamics). Overcoming the aerodynamic/hydrodynamic drag and fluid-dynamic resistance associated with transportation and manufacturing constitutes a significant portion of the energy consumed within the United States, as noted above. However, there has never been a national effort focused on the reduction of aerodynamic drag and fluid-dynamic resistance.

The importance of this matter continues to grow as evident by the growing energy imbalance within the U.S. [1,2] At present the U.S. consumes 35% more energy than it produces and by 2020 the imbalance will increase to 65%. A more dramatic trend is noted for the transportation sector where U. S. oil consumption exceeds the U. S. oil production by 85% in 2002 and it is projected that by 2020 oil consumption will exceed U. S. production by 140%. To address these issues the Department of Transportation (DOT) [11] and the Department of Energy (DOE) [1] have a number of programs investigating a variety of technologies including American fuels and advanced manufacturing processes. However it is clear solving the U.S. energy problem requires technical contributions from all elements of the scientific and engineering sectors.

An objective of this paper is to raise the awareness if these issues within the aerospace community. To this end a discussion of aerodynamic drag reduction research is presented and example aerodynamic drag and fluid-dynamic resistance reduction technologies that have crossed over from one area to another are discussed. A second objective of this paper is to develop an energy-based argument for the discussion of drag and drag management issues in order to bring together a portion of the diverse array of scientific and engineering resources within the United States.

AERODYNAMIC DRAG

As we move into the new millennium, the technical challenges for the Aerospace community are significant and continued success will require that all available information and knowledge be utilized to guide future aircraft development activity. A primary element to this success is the effective management of aircraft aerodynamic drag. However, it is the authors opinion that there exist numerous, self imposed, roadblocks to success. Six of the dominant roadblocks are, (1) the lack of a consistent definition and discussion framework for drag, (2) the acceptance of the false assumption that superposition works in vehicle aerodynamic design, (3) aerodynamic design has become a defensive act in which the focus is on NOT increasing drag, (4) the fundamental characteristics of drag are not known and/or understood, (5) the existing aerodynamic analysis and design tools are not structured or formatted for the study of drag and (6) aerodynamic best practices are not focused on drag.

A first step in correcting these deficiencies is to simplify the discussion of drag into the following two primary areas, skin-friction drag and pressure drag as well as a secondary area of skin-friction/pressure interference drag. This action has the potential to bring together the aeronautics community and bring together the researchers, scientists and engineers addressing

similar topics in other areas of transportation, manufacturing, industrial, chemical, hydrodynamics and bio-medical.

A follow-on step is to set bold drag reduction goals for future air vehicles. These goals must stress the intellectual capacity of the community and thus force the development of an advanced understanding of aerodynamic drag and the development of new technologies and concepts. Suggested goals are; a 50% reduction in both pressure and skin friction drag, from existing levels, and an additional 25% reduction in the skin-friction/pressure interference drag value. A sampling of technologies that may support these goals are; knowledge-based and natural flow design[12], super thick all lifting surfaces[13], virtual and flexible surfaces with locked controlled separation[14] and free surface flows with trapped vortices for pressure drag reduction[15]. Skin friction drag reduction could utilize treated and shaped surfaces[16], reverse flow for viscous thrust[17] flow additives[16], micro vortices[17] and locked separation for repeated laminar flow[17].

Taking a step back from the suggestions offered above and at the same time expanding on this topic allows for the development of the interrelationships between the fundamental forces of nature and the various areas of application, the types of flow, control effectors and flow phenomena affected, see figure 1. The table of figure 1 was developed by reviewing the literature in the areas of aerodynamics[4, 14, 15], transportation[5, 18-20], boundary layer flows[16, 17-27] chemical engineering[28, 29], and industrial engineering[30-33]. This review identified transportation, industrial, and residential /commercial as the primary areas of application for fluid resistance (aerodynamic/hydrodynamic drag) reduction technologies. The sub-areas listed under each primary area are organized in descending order of energy use. The types of flow that occur in the primary application areas are extremely diverse and are characterized by changes in boundary layer state with either organized or random separation for a gas, liquid, or a multi-phase flow medium. Effectors that are used in the subject primary areas to manage these diverse flows are focused on changes to the surface of the solid body or modify the local flow field by adding or removing mass, temperature, or energy. Although there is a significant amount of work in the areas of boundary layer control for drag reduction the primary effector types remain focused on changes to the body surface. The resultant affect of all of these concepts is summarized is the modification of both surface and flow field properties in order to alter the body forces and motion or to manage the flow mixing, motion and noise.

A list of representative aerodynamic drag reduction and/or flow-control effectors for the three primary areas, are provided in figure 2. The information contained in figure 2 was extracted from a thorough review of the available literature and show that only the transportation area utilizes all ten (10) types of effectors identified in figure 1. In contrast the Industrial area utilizes eight (8) of the ten (10) and the Residential/Commercial area is the most limited with three (3) types of flow control effectors. Note, it is not surprising that the number and diversity of drag reduction effectors in each the three primary areas correlates directly with the energy consumed in each area to overcome aerodynamic drag. Another interesting fact is that the control effectors employed in the Transportation area are evenly distributed between skin-friction and pressure drag reduction, whereas, the effectors in the Industrial area are dominated by skin-friction types

Another observation from figure 2 is the fact that several effector types crossover into all three areas of discussion. These crossover effector types are surface shape, surface permeability, and energy addition. Noted in the figure are specific effector concepts that are employed in each of the primary areas.

To provide additional insight into the aerodynamic drag reduction issues facing the community a brief review of the transportation area is presented. The transportation area is selected for this expanded discussion because it is the largest energy user within the U. S. and it is also the area that is most dependent upon drag reduction for economic success. Thus it is the area that employs the largest array of technologies to reduce aerodynamic drag. As shown in figure 1 the transportation area is comprised of ground vehicles, aircraft, watercraft, rail, and pipe systems, with ground, air, and water vehicles comprising 94% of all energy used by transportation in the U. S. [11]. Additionally, ground vehicles use more than six times the energy than the combination of aircraft and watercraft in the U. S..

A top-level drag breakdown for the various transportation vehicles is presented in figure 3 to show the relative importance of pressure drag and skin-friction drag reduction technologies to each vehicle type. This information show that ground

vehicle drag is dominated by pressure drag and aircraft drag and water vehicle drag is comprised of an equal amount of pressure and skin-friction drag. To complete the analysis of the transportation area requires an assessment of the energy used to overcome drag, relative to the total energy used by the vehicle, see figure 4. A review of the available data[10-11] show that ground vehicles use 50% of their energy overcoming aerodynamic drag whereas both aircraft and watercraft use 90% of their energy consumption to overcome drag, see figure 4. Combining the data from figure 3 and 4 show that the impact of skin friction drag and pressure drag to the transportation area is similar. A continuation of this analysis is presented in the following section.

ENERGY USAGE

Presented in figure 5 is a summary of the energy consumption in the U. S. for 2000[1-3]. The figure shows the various sources of energy and the relative magnitude of the imported and exported energy products. The data are presented as quadrillion (QUAD) British thermal units (BTU). A review of the data of figure 5[1-3] shows that largest consumer of energy is transportation, with 99% of the transportation energy derived from petroleum. Note the large amount of energy losses in the generation and transmission of electricity that accounts for 28% of all U. S. energy consumed. The data presented in figures 3 through5 indicate that the largest potential in drag reduction is in the transportation area.

Transportation

The transportation area uses 27% of all energy consumed in the U.S., and the dominant transportation sector is ground vehicles as shown in figure 6[10, 11]. It is interesting to note that the energy use data, see figure 6, for ground vehicles shows that cars and light duty vehicles used 350% more energy than heavy vehicles however a review of the DOT statistics[10] show there are 3,330% more cars and light duty vehicles than heavy vehicles. These data highlight the dramatic difference in vehicle drag and the miles driven per vehicle between light and heavy vehicles. A similar analysis can be made between all ground vehicles and aircraft. The data of figure 7 show that ground vehicles used 1,000% more energy than aircraft and yet surprisingly there are 74,300% more ground vehicles than aircraft. These data can be used to highlight the relative payoff for drag reduction efforts based upon vehicle types. It is clear that the large energy use by an individual aircraft provides an incentive to the community to focus their drag reduction efforts in this area. In a similar fashion the analysis indicates that the drag reduction focus for ground vehicles should be directed towards large trucks and other heavy vehicles that travel a large number of miles each year.

Additional motivation for drag reduction efforts can be drawn from a review of the historical trend in energy usage for the transportation area, as shown in figures 6 and 8[10, 11]. The data of figure 6 are for the complete transportation area and the data of figure 8 show energy consumption for the ground transportation sector. Both figures present data from 1970 to the present and show projected consumption levels to the year 2020. The energy consumption data is presented in terms of millions of barrels of oil/day. Also shown on each figure is a graph of domestic oil production. These data show that transportation energy demands, which are 99% dependent on oil, exceeded U.S. production levels in the 1980s and at present the transportation area consumes 85% more energy (oil) than is produced in the U.S.. The chart also shows that the energy (oil) shortfall will continue to increase and by 2020 consumption will be 140% greater than production.

However, a review of the ground transportation sector data of figure 8 shows that the energy demands of automobiles will remain constant. However, there are dramatic increases in both light and heavy truck energy demands. These projected detrimental energy trends should be viewed as an opportunity for aerodynamic drag reduction efforts. A focused effort on heavy ground vehicles, which have the largest aerodynamic drag levels and have the greatest miles driven per vehicle, will provide a significant payoff in energy savings even with small drag reductions.

Another transportation related point worth noting is related to the energy use for each passenger mile traveled. Presented in figure 9 are data, for the four dominant passenger carriers in the U.S. in the form of a bar chart[10, 11]. These data show results for aircraft, bus, automobile and rail modes of passenger travel. The data show that the most fuel-efficient mode is rail with 3200 BTUs for each passenger mile followed by automobiles at 3700 and aircraft and bus modes being the least energy efficient at 4000.

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INTRODUCTION

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To assess the relative magnitude and impact of these forces on our life a review of the energy consumption associated with the wide array of processes and systems that involve fluid interactions. At first review it is clear that an assessment of the complete role of fluid-dynamics in our life is not only extremely complex but it is beyond the scope of a single paper. To reduce the scope of this topic the following discussion will be limited to fluid dynamic resistance and/or aerodynamic drag and the relationship of drag to energy use in the United States.

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Compared to automobiles the energy values for aircraft and buses are surprising. It would be expected that a large volume carrier would have a lower energy use compared to a low volume and/or single passenger vehicle. These data, in combination with the data of figure 6 through 8, continue to suggest that the focus of drag reduction efforts should be on aircraft and heavy ground vehicles.

Industrial and Residential/Commercial

Although the combination of the Industrial and Residential/Commercial areas consume more than 37% of all U.S. energy[1-3], the percent of the energy expended to overcome aerodynamic drag and/or fluid-dynamic resistance is significantly less than that for the transportation area. To provide a basis for further discussion it is approximated, by a review of Department of Energy (DOE) documents [1-3, 6-9], that 10%, of the subject energy for these two areas is attributed to drag, with the majority of this energy related to the Industrial area. The energy consumption in this area are related to pump losses, pipe flows, fouling, HVAC and duct flows. The review of DOE documents[1-3] also identified a number of other aerodynamic, fluid-dynamic and thermodynamic related issues that consume significant amounts of Industrial energy. Examples of these processes are heating and cooling, electrochemical, boilers, and HVAC. A summary of the various Industrial technologies under consideration is provided in reference 30. In contrast, the energy consumption in the Residential/Commercial area is primarily for lighting and heating, ventilation and cooling (HVAC) [34-37]. While the HVAC sector does offer a limited opportunity for aerodynamic/fluid-dynamic drag reduction the diversity and number of the systems to be addressed may limit the possible gains.

The Industrial area consists of four primary industries; Chemical, Petroleum, Pulp/Paper/ Wood and Iron/Steel[8]. Within each of these areas the dominant use of energy is for heating and one of the primary energy loss areas in heating is fouling. It is estimated that 2% of the Industrial energy is used to overcome fouling. Another area of concern is the fluid-dynamic efficiency of boilers. Boilers consume 37% of the Industrial energy. A third area to focus drag reduction efforts would be in pump efficiency. The present estimate is that 10% of Industrial energy is consumed by pumps. And the final area is pipe flows.

However due to the diversity of the systems, processes and technologies involved in the various sectors of the Industrial area it is extremely difficult to define specific areas to apply drag reduction and/or fluid-dynamic resistance technologies. It is the author's opinion that technologies developed in either the Transportation, Industrial and/or Residential/ Commercial areas would benefit the technology development activities in the other areas or could be applied directly to similar energy reduction needs in other areas.

DESIGNING THE FUTURE

It has been argued that aerodynamic drag and fluid–dynamic resistance reduction technologies have a role in reducing the energy demands of the U.S.. However what is not clear is the magnitude of that role. It is envisioned that by focusing our intellectual capital in aerodynamic and fluid-dynamic issues on the Transportation, Industrial and Residential/ Commercial areas creates the opportunity for significant synergistic interactions among the subject areas and their related disciplines. These interactions have the potential to feed a revolution in energy efficient technologies that will dramatically improve our environment, lead to the development of new energy sources and culminate in radically improved transportation, industrial and manufacturing processes and systems

It is the author's opinion that we cannot get there from here. Although significant progress has been made in the previous two decades in the advancement of computational tools and methods and the development of improved drag and energy reduction technologies the fundamental knowledge and understanding of these issues is based in the past. Similarly, many of the "best practices" and "advanced technologies" in use within the aerodynamics and fluid-dynamics disciplines are also hindered by their reliance on past understanding and biases. A survey of the literature indicates that even though there are significant resources expended in the subject topic area they are spread among a diverse array of technology development activities and among a myriad of government agencies, academia, industries, and professional organizations. These research efforts operate in a competing mode resulting in a fragmented technology development effort. To achieve success in this war on drag and energy the vast array of organizations and discipline research efforts in aerodynamics, transportation, hydrodynamics, wind engineering, environmental sciences, chemistry, medical engineering, combustion, manufacturing, etc. must be brought together under a framework that is focused on a single theme.

Specific goals may be established such as; pressure drag and viscous drag reduction goals of 50%, Another objective is to define consistent drag reduction research "best practices" and goals across all research disciplines and implementation of the processes must be performed in a manner that ensures a significant portion of the success is portable.

As previously mentioned it is estimated that 25% of the total energy consumed in the U.S. is used to overcome drag. Of this, 16% is attributed to Transportation and 9% is related to Industrial and Residential/Commercial energy consumption. If the drag reduction goals discussed above are realized, a 7.85% total energy savings would be achieved. This energy savings is comprised of 5.6% from transportation (note: it is approximated that a 50% drag reduction results in a 35% energy savings) and 2.25% from the combination of Industrial and Residential/ Commercial (note: it is approximated that a 50% drag reduction results in a 25% energy savings) . This energy savings correlates to a yearly cost savings in the $30 Billion dollar range.

Example Drag Reduction Technologies

To achieve success both skin-friction[24, 38-68] and pressure drag[5, 18-21, 69-101] reduction technologies must be developed, applied and transferred across discipline lines. It is fully recognized that it will be extremely difficult to achieve the goals suggested above in a single discipline and it may be impossible to achieve these objectives across multiple discipline areas. However there are a limited number of examples where such success has been achieved. A review of the literature identified a number of successful examples of cross-over technologies. Several of these examples are briefly discussed below.

Pressure

In the area of pressure drag the work of Modi[69], Englar[20], and Bauer[101] are noteworthy for transferring the technology from aircraft to ground vehicles, see figures 10, 11, and 12 respectively. Modi also has also transferred the technology out of the transportation area as documented in reference 69.

There are similarities in the work of Modi and Englar in that they both add momentum to the flow in order to eliminate/control flow separation. Modi employs a moving surface (see figure 10) to achieve this end whereas Englar uses air injection (figure 11). Both have achieved significant drag reductions on the order of 30% with their associated technology

As shown in figure 12 the passive porosity work of Bauer employs a passive feedback mechanism to control flow separation on a blunt base and produce drag reduction of 15%. It is interesting to note that passive porosity technology has its roots in the Industrial area where it was used for vortex shedding control on smoke stacks. This technology was transferred to the aerodynamic community to be used as a liner for wind tunnel walls. Another evolution of the technology occurred in the 1980s and produced a drag reduction concept as documented by the work of Bauer[101].

Two other cross-over technologies are base plates and boattail convolutions used to control base drag, see figures 13 and 14 respectively. The base plate technology was initially developed in 1966 by Bearman to reduce the base drag of blunt trailing edge airfoils 10%[94-95]. This technology then found its way to ground vehicles in 1987 as documented in reference19 providing 15% drag reductions.

The boattail convolutions shown in figure 14 took a much different path[92, 104]. The genesis of the technology came from the Residential/ Commercial sector for HVAC diffuser design and evolved into an aircraft design technology to reduce boattail drag. Experimental aerodynamic data at subsonic speeds have shown drag reductions of 25%[104].

Vortex generators technology is a much more mature, diverse and far reaching in acceptance[61]. Vortex generators were initially developed and applied to aircraft but have been accepted throughout the transportation and Industrial areas. Vortex generators can be found on aircraft, ground vehicles, and watercraft and in diffusers and heat exchangers. Vortex generators are designed as both active and passive devices, mechanical and pneumatic devices and operate on the external flow or are submerged completely within the boundary layer.

Additional extensions/crossovers of each of these technologies is possible with clear applications to diffusers, ducting, pipes, valves, heat exchangers to name a few. There are also other aerodynamic technologies such as thrust vectoring[85] self activating flaps[72], oscillating flow spoilers[74], and pneumatic spoilers[82] that would improve the performance of nozzles, dust and pipe flow, and heat exchangers.

Skin-Friction

A literature survey of the skin-friction drag area highlights the diversity and magnitude of the research being performed by a broad cross section of Industries and government agencies[24, 38-69]. The review indicated that the area of skin-friction drag reduction is typically divided into two efforts, those focused on maintaining a laminar boundary layer and efforts reducing the turbulent boundary-layer skin-friction drag. The review also indicated that there are a number of excellent summary reports on the subject matter. As a result of this review it is determined that an additional review is beyond the scope of this paper. The author recognizes the importance and the diversity and complexity of this topic area. The research performed in this area is highly competitive and appears to be driven by economic factors that dominate the Industrial area within the U.S,

However there are several examples worth noting. One of the skin friction drag cross over technologies is riblets[65]. Riblets were conceived from observations of nature[102-105], specifically the skin of a shark, and they were originally developed for aircraft applications. They have found their way onto watercraft and into pipes and ducts. It is interesting to note that they have not achieved universal success in the aerospace community but a version of the technology is used in the Industrial area for pipe flows [24].

Other skin friction drag reduction technologies are laminar flow control with boundary layer removal or wall cooling[66], turbulent boundary layer polymer addition and bubble injection[59], and wall oscillation and compliant walls[41].

CONCLUDING REMARKS

A force-based / energy-based assessment of the role of fluid-dynamics in our life is presented with a focus on fluid dynamic resistance and/or aerodynamic drag and the relationship to energy use in the United States. Existing data indicates that up to 25% of the total energy consumed in the United States is used to overcome aerodynamic drag, 27% of the total energy used in the United States is consumed by transportation systems, and 60% of the transportation energy or 16% of the total energy consumed in the United States is used to overcome aerodynamic drag in transportation systems. It was also shown that there is an additional 9% of the total energy consumed in the United States that is spent overcoming aerodynamic drag (fluid-dynamic resistance) in non-transportation industries. Drag reduction goals of 50% are proposed and discussed which if realized would produce a 7.85% total energy savings. This energy savings correlates to a yearly cost savings in the $30 Billion dollar range. A number of programmatic and technical challenges are defined that support the objectives outlined. Additionally there is are some comments offered to the reader on drag reduction technologies that have successfully crossed over from one industry to another.

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Aerodynamic Drag and Drag Reduction: Energy and Energy Savings (Invited)

Richard M. Wood
NASA Langley Research Center
Hampton, Virginia

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Aerodynamic Drag and Drag Reduction: Energy and Energy Savings

Richard M. Wood

ABSTRACT

An assessment of the role of fluid dynamic resistance and/or aerodynamic drag and the relationship to energy use in the United States is presented. Existing data indicates that up to 25% of the total energy consumed in the United States is used to overcome aerodynamic drag, 27% of the total energy used in the United States is consumed by transportation systems, and 60% of the transportation energy or 16% of the total energy consumed in the United States is used to overcome aerodynamic drag in transportation systems. Drag reduction goals of 50% are proposed and discussed which if realized would produce a 7.85% total energy savings. This energy savings correlates to a yearly cost savings in the $30Billion dollar range.

INTRODUCTION

There are a number of fundamental forces in nature that influence our way of life, three of these forces are; gravity, fluid-dynamics (i.e. wind and water forces) and solid mechanics (i.e. earthquakes). It is argued that after gravity, fluid-dynamics is nature's most prevalent force on earth. We spend our life interacting with a variety of fluids from the air we breath and water we drink to the storms we shelter from. Fluid-dynamic forces have a significant influence on transportation, recreation and sport. A review of data from the Department of Energy (DOE) indicate that there are numerous fluid interactions that influence the energy consumption of our transportation systems, manufacturing processes and heating and cooling needs. [1-3].

To assess the relative magnitude and impact of these forces on our life a review of the energy consumption associated with the wide array of processes and systems that involve fluid interactions. At first review it is clear that an assessment of the complete role of fluid-dynamics in our life is not only extremely complex but it is beyond the scope of a single paper. To reduce the scope of this topic the following discussion will be limited to fluid dynamic resistance and/or aerodynamic drag and the relationship of drag to energy use in the United States.

To help clarify the focus of this discussion the following definition of fluid-dynamic resistance is offered to the reader. Fluid-dynamic resistance is defined as the force resulting from the interaction of a fluid with a solid object that opposes the desired motion of the fluid or solid object. It is important to note that the term fluid-dynamic resistance will be used interchangeably with aerodynamic drag. The purpose of relating the discussion to aerodynamics is simply a refection of the author's area of expertise. Note, the energy used to overcome gravity will not be discussed.

A review of the literature show that previous discussions of aerodynamic drag have been either discipline focused [4, 5] such as aircraft or ground vehicles; in order to accentuate the unique character and features of a research area or they have been narrower in scope by focusing on a single vehicle class such as a transport or a fighter aircraft. This discussion, while focusing on aerodynamic drag, will not limit the discussion to aircraft drag reduction, but will review the general topic of fluid-dynamic resistance and/or aerodynamic drag and relate these observations to energy consumption. The discussion of energy consumption provides a direct connection to the economic impact of the technologies that are capable of reducing aerodynamic drag and it provides a technical connection to other disciplines and industries that benefit from aerodynamic drag reduction technologies.

The relationship between aerodynamic drag and energy use in the United States (US) can be obtained by reviewing data from the Department of Transportation (DOT) and the DOE[1-3, 6-11]. An analysis of the DOE and DOT energy data coupled with a fundamental understanding of the role of fluid-dynamic resistance on transportation, manufacturing and heating/cooling requirements allows for the following estimates of energy use in the United States (U.S.). Note, the listed estimates will be discussed further in the following section of the paper.

- 25% of the total energy consumed in the United States is used to overcome aerodynamic drag.
- 27% of the total energy used in the United States is consumed by transportation systems
- 60% of the transportation energy or 16% of the total energy consumed in the United States is used to overcome aerodynamic drag in transportation systems.

These estimates indicate that, in addition to transportation, the Industry and Residential/ Commercial areas consume an additional 9% of the total energy used in the United States at overcome aerodynamic drag (fluid-dynamic resistance). This observation highlights the importance of including non-transportation industries and technologies in the discussion of aerodynamic drag.

All transportation systems and manufacturing processes involve either the movement of solid structures through fluids or the movement of fluids past solid structures (i.e. aerodynamics, hydrodynamics and fluid-dynamics). Overcoming the aerodynamic/hydrodynamic drag and fluid-dynamic resistance associated with transportation and manufacturing constitutes a significant portion of the energy consumed within the United States, as noted above. However, there has never been a national effort focused on the reduction of aerodynamic drag and fluid-dynamic resistance.

The importance of this matter continues to grow as evident by the growing energy imbalance within the U.S. [1,2]. At present the U.S. consumes 35% more energy than it produces and by 2020 the imbalance will increase to 65%. A more dramatic trend is noted for the transportation sector where U. S. oil consumption exceeds the U. S. oil production by 85% in 2002 and it is projected that by 2020 oil consumption will exceed U. S. production by 140%. To address these issues the Department of Transportation (DOT) [11] and the Department of Energy (DOE) [1] have a number of programs investigating a variety of technologies including American fuels and advanced manufacturing processes. However it is clear solving the U.S. energy problem requires technical contributions from all elements of the scientific and engineering sectors.

An objective of this paper is to raise the awareness if these issues within the aerospace community. To this end a discussion of aerodynamic drag reduction research is presented and example aerodynamic drag and fluid-dynamic resistance reduction technologies that have crossed over from one area to another are discussed. A second objective of this paper is to develop an energy-based argument for the discussion of drag and drag management issues in order to bring together a portion of the diverse array of scientific and engineering resources within the United States.

AERODYNAMIC DRAG

As we move into the new millennium, the technical challenges for the Aerospace community are significant and continued success will require that all available information and knowledge be utilized to guide future aircraft development activity. A primary element to this success is the effective management of aircraft aerodynamic drag. However, it is the authors opinion that there exist numerous, self imposed, roadblocks to success. Six of the dominant roadblocks are, (1) the lack of a consistent definition and discussion framework for drag, (2) the acceptance of the false assumption that superposition works in vehicle aerodynamic design, (3) aerodynamic design has become a defensive act in which the focus is on NOT increasing drag, (4) the fundamental characteristics of drag are not known and/or understood, (5) the existing aerodynamic analysis and design tools are not structured or formatted for the study of drag and (6) aerodynamic best practices are not focused on drag.

A first step in correcting these deficiencies is to simplify the discussion of drag into the following two primary areas, skin-friction drag and pressure drag as well as a secondary area of skin-friction/pressure interference drag. This action has the potential to bring together the aeronautics community and bring together the researchers, scientists and engineers addressing

similar topics in other areas of transportation, manufacturing, industrial, chemical, hydrodynamics and bio-medical.

A follow-on step is to set bold drag reduction goals for future air vehicles. These goals must stress the intellectual capacity of the community and thus force the development of an advanced understanding of aerodynamic drag and the development of new technologies and concepts. Suggested goals are; a 50% reduction in both pressure and skin friction drag, from existing levels, and an additional 25% reduction in the skin-friction/pressure interference drag value. A sampling of technologies that may support these goals are; knowledge-based and natural flow design[12], super thick all lifting surfaces[13], virtual and flexible surfaces with locked controlled separation[14] and free surface flows with trapped vortices for pressure drag reduction[15]. Skin friction drag reduction could utilize treated and shaped surfaces[16], reverse flow for viscous thrust[17] flow additives[16], micro vortices[17] and locked separation for repeated laminar flow[17].

Taking a step back from the suggestions offered above and at the same time expanding on this topic allows for the development of the interrelationships between the fundamental forces of nature and the various areas of application, the types of flow, control effectors and flow phenomena affected, see figure 1. The table of figure 1 was developed by reviewing the literature in the areas of aerodynamics[4, 14, 15], transportation[5, 18-20], boundary layer flows[16, 17-27] chemical engineering[28, 29], and industrial engineering[30-33]. This review identified transportation, industrial, and residential /commercial as the primary areas of application for fluid resistance (aerodynamic/hydrodynamic drag) reduction technologies. The sub-areas listed under each primary area are organized in descending order of energy use. The types of flow that occur in the primary application areas are extremely diverse and are characterized by changes in boundary layer state with either organized or random separation for a gas, liquid, or a multi-phase flow medium. Effectors that are used in the subject primary areas to manage these diverse flows are focused on changes to the surface of the solid body or modify the local flow field by adding or removing mass, temperature, or energy. Although there is a significant amount of work in the areas of boundary layer control for drag reduction the primary effector types remain focused on changes to the body surface. The resultant affect of all of these concepts is summarized is the modification of both surface and flow field properties in order to alter the body forces and motion or to manage the flow mixing, motion and noise.

A list of representative aerodynamic drag reduction and/or flow-control effectors for the three primary areas, are provided in figure 2. The information contained in figure 2 was extracted from a thorough review of the available literature and show that only the transportation area utilizes all ten (10) types of effectors identified in figure 1. In contrast the Industrial area utilizes eight (8) of the ten (10) and the Residential/Commercial area is the most limited with three (3) types of flow control effectors. Note, it is not surprising that the number and diversity of drag reduction effectors in each the three primary areas correlates directly with the energy consumed in each area to overcome aerodynamic drag. Another interesting fact is that the control effectors employed in the Transportation area are evenly distributed between skin-friction and pressure drag reduction, whereas, the effectors in the Industrial area are dominated by skin-friction types

Another observation from figure 2 is the fact that several effector types crossover into all three areas of discussion. These crossover effector types are surface shape, surface permeability, and energy addition. Noted in the figure are specific effector concepts that are employed in each of the primary areas.

To provide additional insight into the aerodynamic drag reduction issues facing the community a brief review of the transportation area is presented. The transportation area is selected for this expanded discussion because it is the largest energy user within the U. S. and it is also the area that is most dependent upon drag reduction for economic success. Thus it is the area that employs the largest array of technologies to reduce aerodynamic drag. As shown in figure 1 the transportation area is comprised of ground vehicles, aircraft, watercraft, rail, and pipe systems, with ground, air, and water vehicles comprising 94% of all energy used by transportation in the U. S. [11]. Additionally, ground vehicles use more than six times the energy than the combination of aircraft and watercraft in the U. S..

A top-level drag breakdown for the various transportation vehicles is presented in figure 3 to show the relative importance of pressure drag and skin-friction drag reduction technologies to each vehicle type. This information show that ground

vehicle drag is dominated by pressure drag and aircraft drag and water vehicle drag is comprised of an equal amount of pressure and skin-friction drag. To complete the analysis of the transportation area requires an assessment of the energy used to overcome drag, relative to the total energy used by the vehicle, see figure 4. A review of the available data[10-11] show that ground vehicles use 50% of their energy overcoming aerodynamic drag whereas both aircraft and watercraft use 90% of their energy consumption to overcome drag, see figure 4. Combining the data from figure 3 and 4 show that the impact of skin friction drag and pressure drag to the transportation area is similar. A continuation of this analysis is presented in the following section.

ENERGY USAGE

Presented in figure 5 is a summary of the energy consumption in the U. S. for 2000[1-3]. The figure shows the various sources of energy and the relative magnitude of the imported and exported energy products. The data are presented as quadrillion (QUAD) British thermal units (BTU). A review of the data of figure 5[1-3] shows that largest consumer of energy is transportation, with 99% of the transportation energy derived from petroleum. Note the large amount of energy losses in the generation and transmission of electricity that accounts for 28% of all U. S. energy consumed. The data presented in figures 3 through5 indicate that the largest potential in drag reduction is in the transportation area.

Transportation

The transportation area uses 27% of all energy consumed in the U.S., and the dominant transportation sector is ground vehicles as shown in figure 6[10, 11]. It is interesting to note that the energy use data, see figure 6, for ground vehicles shows that cars and light duty vehicles used 350% more energy than heavy vehicles however a review of the DOT statistics[10] show there are 3,330% more cars and light duty vehicles than heavy vehicles. These data highlight the dramatic difference in vehicle drag and the miles driven per vehicle between light and heavy vehicles. A similar analysis can be made between all ground vehicles and aircraft. The data of figure 7 show that ground vehicles used 1,000% more energy than aircraft and yet surprisingly there are 74,300% more ground vehicles than aircraft. These data can be used to highlight the relative payoff for drag reduction efforts based upon vehicle types. It is clear that the large energy use by an individual aircraft provides an incentive to the community to focus their drag reduction efforts in this area. In a similar fashion the analysis indicates that the drag reduction focus for ground vehicles should be directed towards large trucks and other heavy vehicles that travel a large number of miles each year.

Additional motivation for drag reduction efforts can be drawn from a review of the historical trend in energy usage for the transportation area, as shown in figures 6 and 8[10, 11]. The data of figure 6 are for the complete transportation area and the data of figure 8 show energy consumption for the ground transportation sector. Both figures present data from 1970 to the present and show projected consumption levels to the year 2020. The energy consumption data is presented in terms of millions of barrels of oil/day. Also shown on each figure is a graph of domestic oil production. These data show that transportation energy demands, which are 99% dependent on oil, exceeded U.S. production levels in the 1980s and at present the transportation area consumes 85% more energy (oil) than is produced in the U.S.. The chart also shows that the energy (oil) shortfall will continue to increase and by 2020 consumption will be 140% greater than production.

However, a review of the ground transportation sector data of figure 8 shows that the energy demands of automobiles will remain constant. However, there are dramatic increases in both light and heavy truck energy demands. These projected detrimental energy trends should be viewed as an opportunity for aerodynamic drag reduction efforts. A focused effort on heavy ground vehicles, which have the largest aerodynamic drag levels and have the greatest miles driven per vehicle, will provide a significant payoff in energy savings even with small drag reductions.

Another transportation related point worth noting is related to the energy use for each passenger mile traveled. Presented in figure 9 are data, for the four dominant passenger carriers in the U.S. in the form of a bar chart[10, 11]. These data show results for aircraft, bus, automobile and rail modes of passenger travel. The data show that the most fuel-efficient mode is rail with 3200 BTUs for each passenger mile followed by automobiles at 3700 and aircraft and bus modes being the least energy efficient at 4000.

Compared to automobiles the energy values for aircraft and buses are surprising. It would be expected that a large volume carrier would have a lower energy use compared to a low volume and/or single passenger vehicle. These data, in combination with the data of figure 6 through 8, continue to suggest that the focus of drag reduction efforts should be on aircraft and heavy ground vehicles.

Industrial and Residential/Commercial

Although the combination of the Industrial and Residential/Commercial areas consume more than 37% of all U.S. energy[1-3], the percent of the energy expended to overcome aerodynamic drag and/or fluid-dynamic resistance is significantly less than that for the transportation area. To provide a basis for further discussion it is approximated, by a review of Department of Energy (DOE) documents [1-3, 6-9], that 10%, of the subject energy for these two areas is attributed to drag, with the majority of this energy related to the Industrial area. The energy consumption in this area are related to pump losses, pipe flows, fouling, HVAC and duct flows. The review of DOE documents[1-3] also identified a number of other aerodynamic, fluid-dynamic and thermodynamic related issues that consume significant amounts of Industrial energy. Examples of these processes are heating and cooling, electrochemical, boilers, and HVAC. A summary of the various Industrial technologies under consideration is provided in reference 30. In contrast, the energy consumption in the Residential/Commercial area is primarily for lighting and heating, ventilation and cooling (HVAC) [34-37]. While the HVAC sector does offer a limited opportunity for aerodynamic/fluid-dynamic drag reduction the diversity and number of the systems to be addressed may limit the possible gains.

The Industrial area consists of four primary industries; Chemical, Petroleum, Pulp/Paper/Wood and Iron/Steel[8]. Within each of these areas the dominant use of energy is for heating and one of the primary energy loss areas in heating is fouling. It is estimated that 2% of the Industrial energy is used to overcome fouling. Another area of concern is the fluid-dynamic efficiency of boilers. Boilers consume 37% of the Industrial energy. A third area to focus drag reduction efforts would be in pump efficiency. The present estimate is that 10% of Industrial energy is consumed by pumps. And the final area is pipe flows.

However due to the diversity of the systems, processes and technologies involved in the various sectors of the Industrial area it is extremely difficult to define specific areas to apply drag reduction and/or fluid-dynamic resistance technologies. It is the author's opinion that technologies developed in either the Transportation, Industrial and/or Residential/Commercial areas would benefit the technology development activities in the other areas or could be applied directly to similar energy reduction needs in other areas.

DESIGNING THE FUTURE

It has been argued that aerodynamic drag and fluid–dynamic resistance reduction technologies have a role in reducing the energy demands of the U.S.. However what is not clear is the magnitude of that role. It is envisioned that by focusing our intellectual capital in aerodynamic and fluid-dynamic issues on the Transportation, Industrial and Residential/ Commercial areas creates the opportunity for significant synergistic interactions among the subject areas and their related disciplines. These interactions have the potential to feed a revolution in energy efficient technologies that will dramatically improve our environment, lead to the development of new energy sources and culminate in radically improved transportation, industrial and manufacturing processes and systems

It is the author's opinion that we cannot get there from here. Although significant progress has been made in the previous two decades in the advancement of computational tools and methods and the development of improved drag and energy reduction technologies the fundamental knowledge and understanding of these issues is based in the past. Similarly, many of the "best practices" and "advanced technologies" in use within the aerodynamics and fluid-dynamics disciplines are also hindered by their reliance on past understanding and biases. A survey of the literature indicates that even though there are significant resources expended in the subject topic area they are spread among a diverse array of technology development activities and among a myriad of government agencies, academia, industries, and professional organizations. These research efforts operate in a competing mode resulting in a fragmented technology development effort. To achieve success in this war on drag and energy the vast array of organizations and discipline research efforts in aerodynamics, transportation, hydrodynamics, wind engineering, environmental sciences, chemistry, medical engineering, combustion, manufacturing, etc. must be brought together under a framework that is focused on a single theme.

Specific goals may be established such as; pressure drag and viscous drag reduction goals of 50%, Another objective is to define consistent drag reduction research "best practices" and goals across all research disciplines and implementation of the processes must be performed in a manner that ensures a significant portion of the success is portable.

As previously mentioned it is estimated that 25% of the total energy consumed in the U.S. is used to overcome drag. Of this, 16% is attributed to Transportation and 9% is related to Industrial and Residential/Commercial energy consumption. If the drag reduction goals discussed above are realized, a 7.85% total energy savings would be achieved. This energy savings is comprised of 5.6% from transportation (note: it is approximated that a 50% drag reduction results in a 35% energy savings) and 2.25% from the combination of Industrial and Residential/ Commercial (note: it is approximated that a 50% drag reduction results in a 25% energy savings) . This energy savings correlates to a yearly cost savings in the $30 Billion dollar range.

Example Drag Reduction Technologies

To achieve success both skin-friction[24, 38-68] and pressure drag[5, 18-21, 69-101] reduction technologies must be developed, applied and transferred across discipline lines. It is fully recognized that it will be extremely difficult to achieve the goals suggested above in a single discipline and it may be impossible to achieve these objectives across multiple discipline areas. However there are a limited number of examples where such success has been achieved. A review of the literature identified a number of successful examples of cross-over technologies. Several of these examples are briefly discussed below.

Pressure

In the area of pressure drag the work of Modi[69], Englar[20], and Bauer[101] are noteworthy for transferring the technology from aircraft to ground vehicles, see figures 10, 11, and 12 respectively. Modi also has also transferred the technology out of the transportation area as documented in reference 69.

There are similarities in the work of Modi and Englar in that they both add momentum to the flow in order to eliminate/control flow separation. Modi employs a moving surface (see figure 10) to achieve this end whereas Englar uses air injection (figure 11). Both have achieved significant drag reductions on the order of 30% with their associated technology

As shown in figure 12 the passive porosity work of Bauer employs a passive feedback mechanism to control flow separation on a blunt base and produce drag reduction of 15%. It is interesting to note that passive porosity technology has its roots in the Industrial area where it was used for vortex shedding control on smoke stacks. This technology was transferred to the aerodynamic community to be used as a liner for wind tunnel walls. Another evolution of the technology occurred in the 1980s and produced a drag reduction concept as documented by the work of Bauer[101].

Two other cross-over technologies are base plates and boattail convolutions used to control base drag, see figures 13 and 14 respectively. The base plate technology was initially developed in 1966 by Bearman to reduce the base drag of blunt trailing edge airfoils 10%[94-95]. This technology then found its way to ground vehicles in 1987 as documented in reference19 providing 15% drag reductions.

The boattail convolutions shown in figure 14 took a much different path[92, 104]. The genesis of the technology came from the Residential/ Commercial sector for HVAC diffuser design and evolved into an aircraft design technology to reduce boattail drag. Experimental aerodynamic data at subsonic speeds have shown drag reductions of 25%[104].

Vortex generators technology is a much more mature, diverse and far reaching in acceptance[61]. Vortex generators were initially developed and applied to aircraft but have been accepted throughout the transportation and Industrial areas. Vortex generators can be found on aircraft, ground vehicles, and watercraft and in diffusers and heat exchangers. Vortex generators are designed as both active and passive devices, mechanical and pneumatic devices and operate on the external flow or are submerged completely within the boundary layer.

Additional extensions/crossovers of each of these technologies is possible with clear applications to diffusers, ducting, pipes, valves, heat exchangers to name a few. There are also other aerodynamic technologies such as thrust vectoring[85] self activating flaps[72], oscillating flow spoilers[74], and pneumatic spoilers[82] that would improve the performance of nozzles, dust and pipe flow, and heat exchangers.

Skin-Friction

A literature survey of the skin-friction drag area highlights the diversity and magnitude of the research being performed by a broad cross section of Industries and government agencies[24, 38-69]. The review indicated that the area of skin-friction drag reduction is typically divided into two efforts, those focused on maintaining a laminar boundary layer and efforts reducing the turbulent boundary-layer skin-friction drag. The review also indicated that there are a number of excellent summary reports on the subject matter. As a result of this review it is determined that an additional review is beyond the scope of this paper. The author recognizes the importance and the diversity and complexity of this topic area. The research performed in this area is highly competitive and appears to be driven by economic factors that dominate the Industrial area within the U.S,

However there are several examples worth noting. One of the skin friction drag cross over technologies is riblets[65]. Riblets were conceived from observations of nature[102-105], specifically the skin of a shark, and they were originally developed for aircraft applications. They have found their way onto watercraft and into pipes and ducts. It is interesting to note that they have not achieved universal success in the aerospace community but a version of the technology is used in the Industrial area for pipe flows [24].

Other skin friction drag reduction technologies are laminar flow control with boundary layer removal or wall cooling[66], turbulent boundary layer polymer addition and bubble injection[59], and wall oscillation and compliant walls[41].

CONCLUDING REMARKS

A force-based / energy-based assessment of the role of fluid-dynamics in our life is presented with a focus on fluid dynamic resistance and/or aerodynamic drag and the relationship to energy use in the United States. Existing data indicates that up to 25% of the total energy consumed in the United States is used to overcome aerodynamic drag, 27% of the total energy used in the United States is consumed by transportation systems, and 60% of the transportation energy or 16% of the total energy consumed in the United States is used to overcome aerodynamic drag in transportation systems. It was also shown that there is an additional 9% of the total energy consumed in the United States that is spent overcoming aerodynamic drag (fluid-dynamic resistance) in non-transportation industries. Drag reduction goals of 50% are proposed and discussed which if realized would produce a 7.85% total energy savings. This energy savings correlates to a yearly cost savings in the $30 Billion dollar range. A number of programmatic and technical challenges are defined that support the objectives outlined. Additionally there is are some comments offered to the reader on drag reduction technologies that have successfully crossed over from one industry to another.

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Force in Nature	Area of Application	Flow Type	Effector Type	Phenomena	Purpose
Gravity **Fluid Resistance** Mechanical	**Transportation** -Ground -Air -Water -Rail -Pipe **Industrial** - Petroleum - Chemical - Pulp and Paper - Metals **Residential /Commercial** - HVAC	**Attached** - Laminar - Turbulent - Transitional **Separated** - Organized - Random **Fluid** - Gas - Liquid - Multi-Phase	**Surface** - Shape/Texture - Motion - Permeability - Temperature - Coating **Flow** - Addition - Removal **Additives** - Mass - Temperature - Energy	**Surface** - Friction - Pressure - Heat Transfer **Flow** - Mass - Pressure - Structure	**Body** - Force - Motion **Flow** - Noise - Mixing - Motion

Figure 1. Interrelationship between forces, applications, flows, effectors and flow phenomena.

Transportation	Industrial	Residential / Commercial
Surface • Shape - Truck Cab Fairing • Motion - Rotating Cylinder • Permeability - Passive Porosity • Temperature - Laminar Flow Control • Coating - Polymers, Watercraft **Flow** • Addition - Base Area Bleed • Removal - Airfoil Shock Control **Additives** • Mass - Circulation Control • Temperature - Base Burning • Energy - Vortex Generators	**Surface** • Shape - Piping and Diffusers • Permeability - Passive Porosity • Coating - Polymers, Piping **Flow** • Addition - Slot Injection • Removal - Separation Control **Additives** • Mass - Polymers in Piping • Temperature - Base Burning • Energy - Vortex Generators	**Surface** • Shape - Fan Diffusers • Permeability - Screens **Flow** **Additives** • Energy - Vortex Generators

Figure 2. Listing of representative drag reduction flow control effectors.

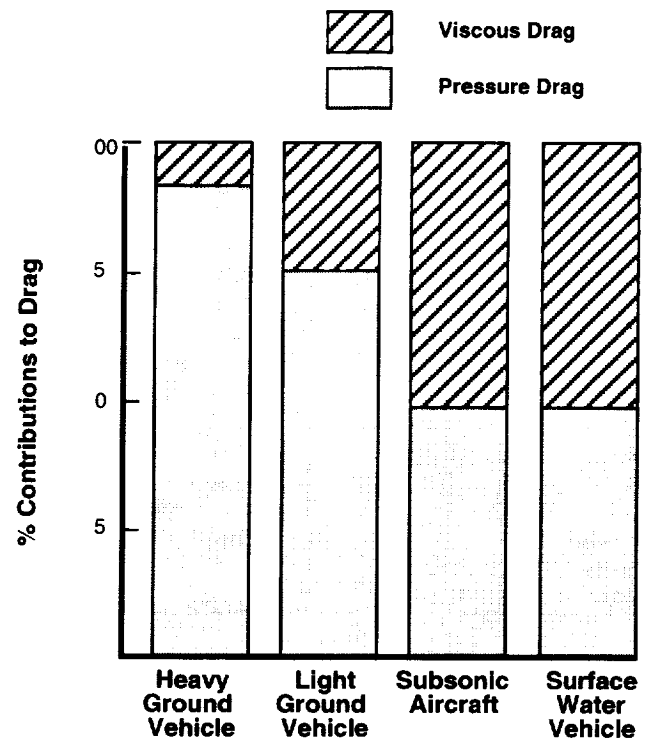


Figure 3. Distribution of drag forces for ground, air and water vehicles.

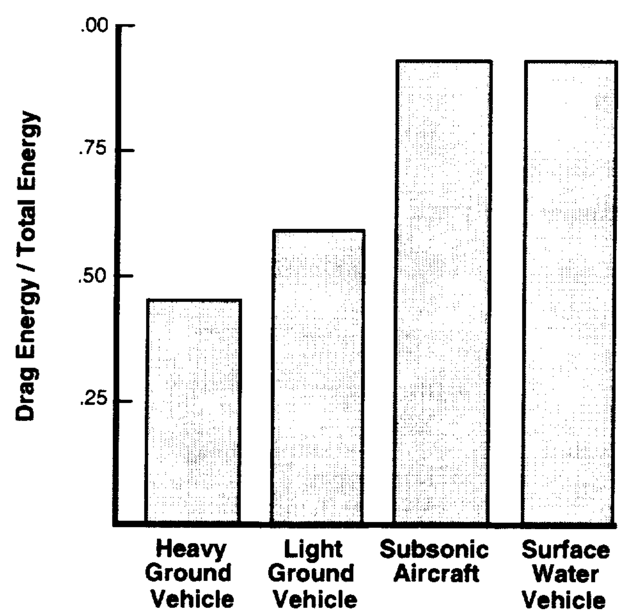


Figure 4. Energy consumed to overcome drag for ground, air, and water vehicles.

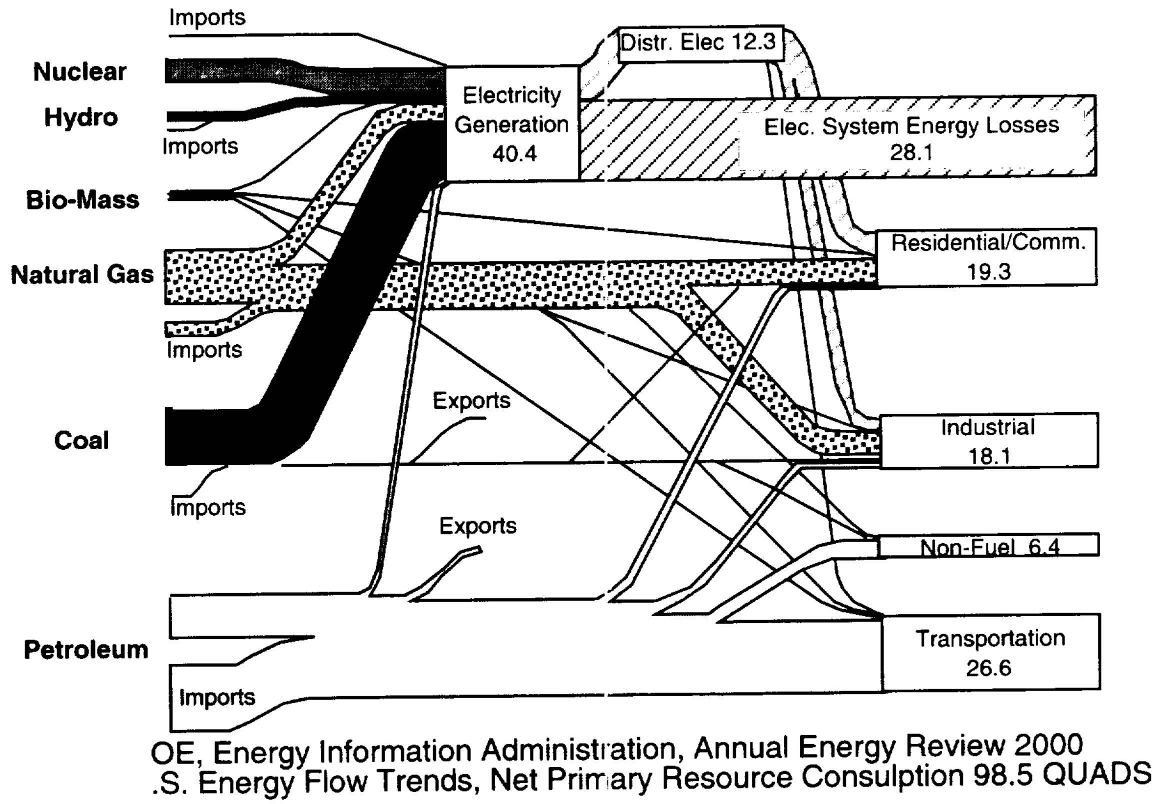


Figure 5 Energy flow trends for the United states in 2000.

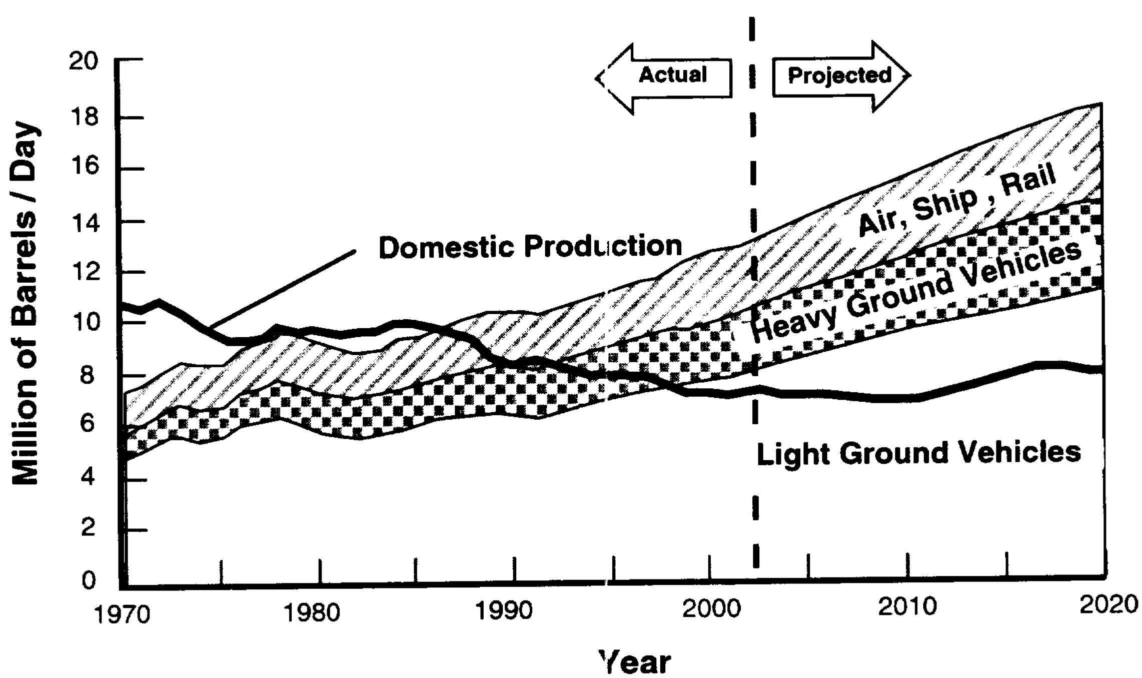


Figure 6. Historical trend in transportation energy consumption.

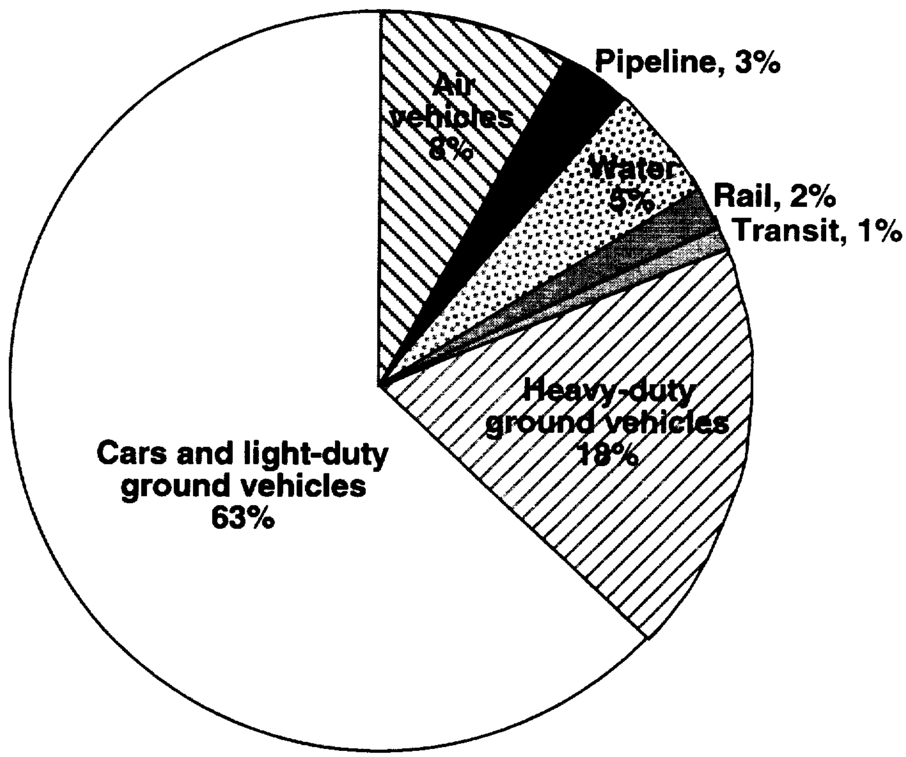


Figure 7. Distribution of transportation energy consumption.

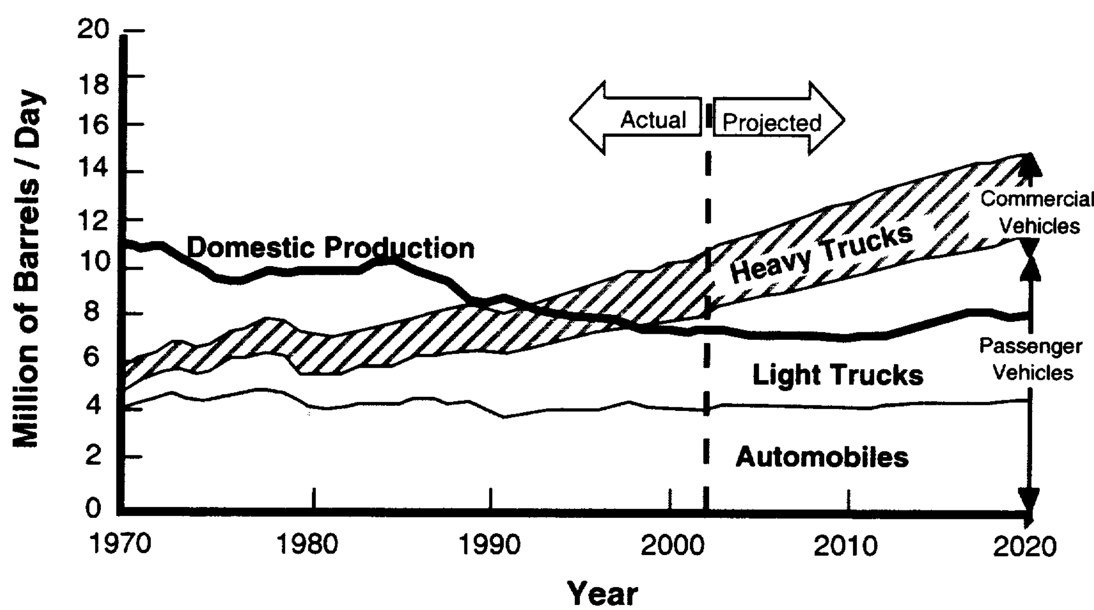


Figure 8. Historical trend in transportation energy consumption for ground vehicles.

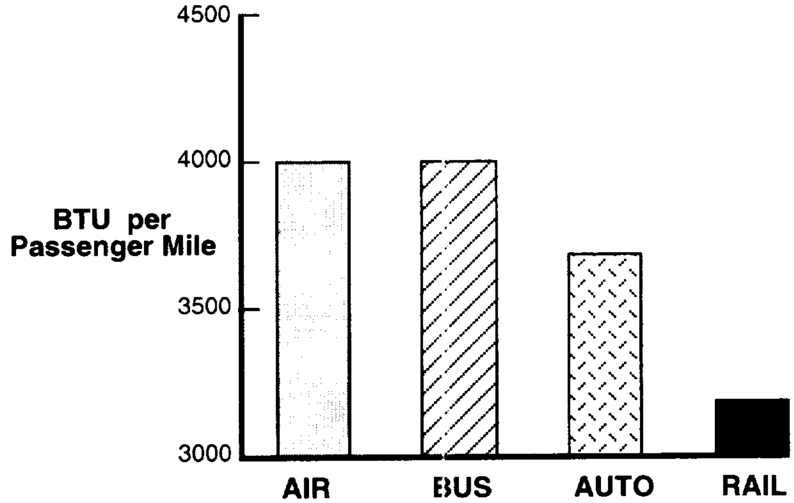


Figure 9. Energy loading per passenger mile traveled for air and ground transportation systems.

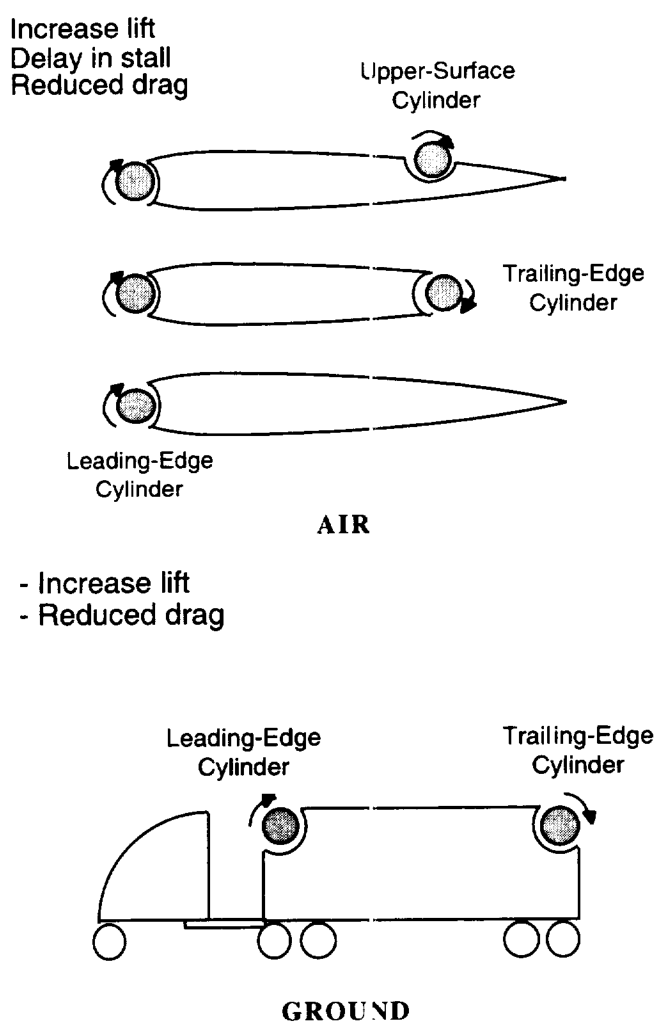
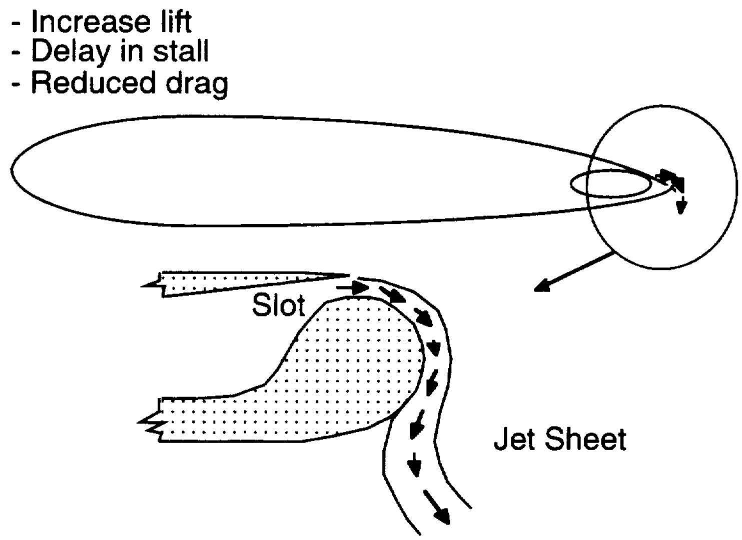
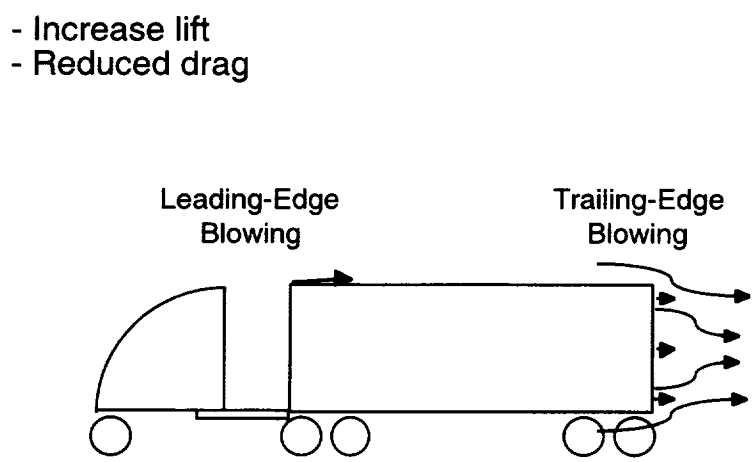


Figure 10. Schematic of mechanical based momentum injection technology applied to air and ground vehicles.

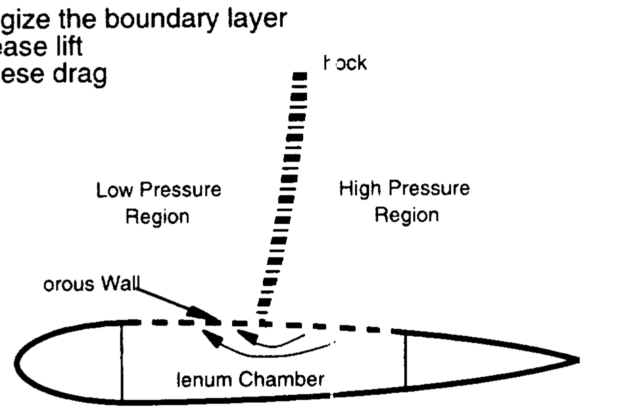


AIR

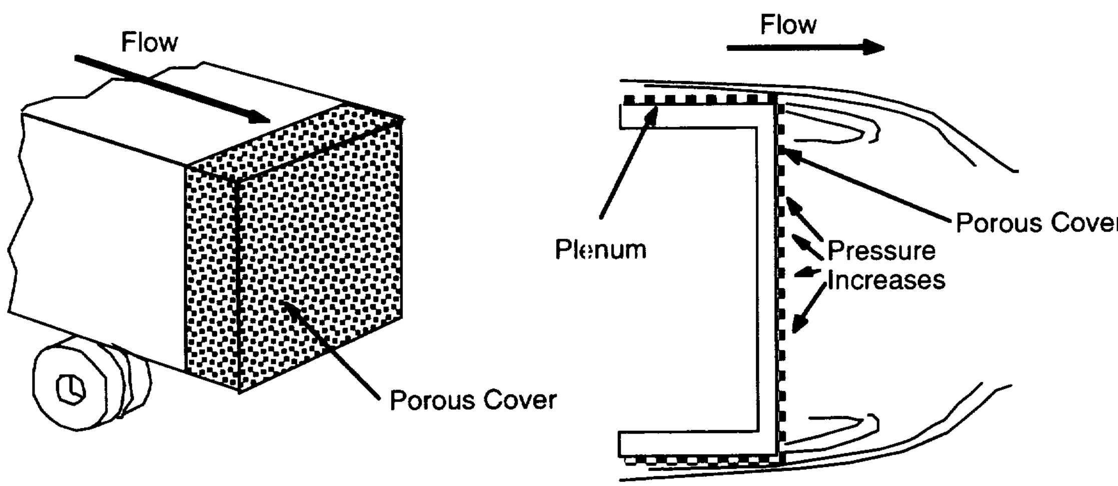


GROUND

Figure 11. Schematics of circulation control technology applied to air and ground vehicles, reference 20.



AIR



GROUND

Figure 12. Schematics of passive porosity technology for air and ground vehicles.

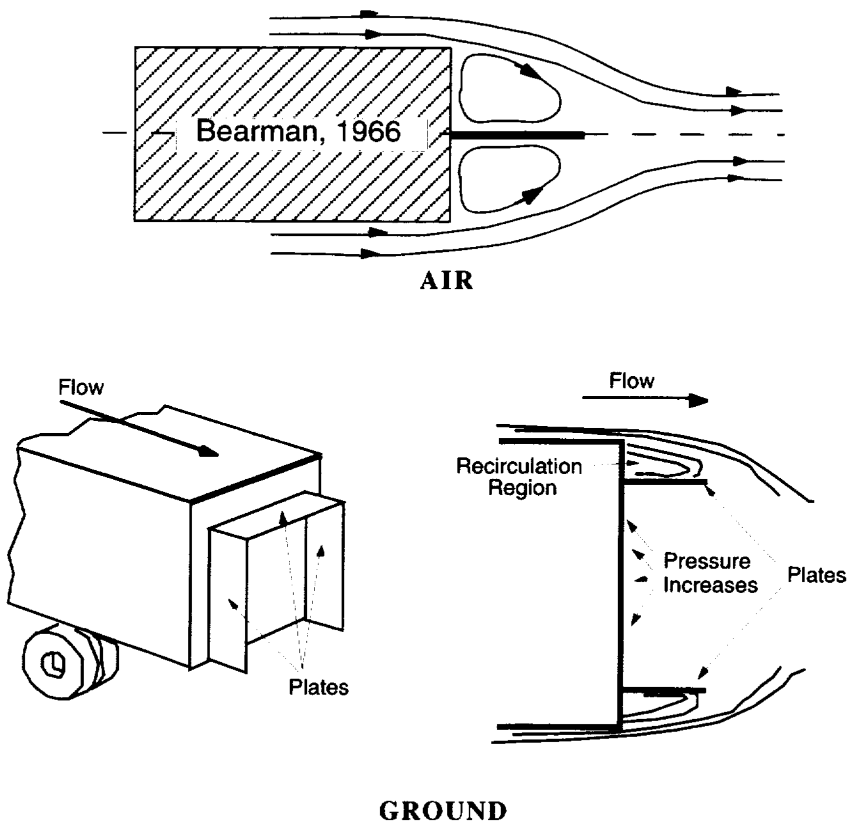


Figure 13. Vortex capture plates technology applied to air and ground vehicles.

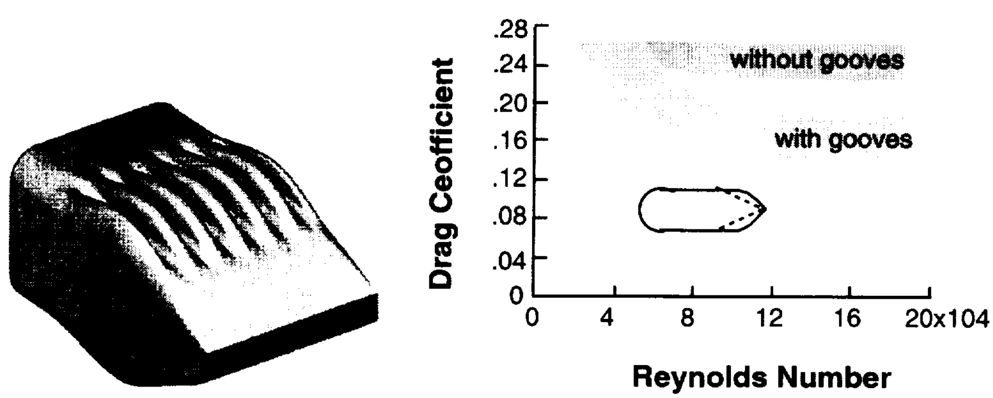


Figure 14. Convolution technology applied to boattail geometries.