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Experimental and Theoretical Investigations of Compressible Boundary Layers

The motivation of this research is to evaluate the current turbulence models available in order to predict both the velocity and the temperature in a compressible turbulent boundary layer. The difficulty behind measuring both variables independently is due to a coupling effect that occurs at high speeds. Once the Mach number exceeds approximately 0.3, compressibility effects in the flow cannot be overlooked. The density variations become significant and heat transfer plays a substantial role in altering the dynamics of the flow. Physical properties, such as the specific heat capacities, the viscosity and the thermal conductivity, which are often considered as being constant, now vary with respect to temperature, creating the aforementioned strong coupling between the velocity and the temperature fields.

Numerous researchers have attempted to characterize turbulent boundary layers at supersonic speeds. The Reynolds analogy, also called the Reynolds analogy of the first kind, was first introduced to relate the heat transfer to the momentum transfer occurring in the flow. However, this analogy contains two weaknesses: it first assumes that both the temperature and the velocity have the exact same distribution and secondly it requires for the Prandtl number to be equal to unity [1].

In light of these shortcomings, Young and Morkovin [2] formulated a different set of equations named the Strong Reynolds Analogy (SRA) – or the Reynolds analogy of the second kind – in order to more accurately correlate the velocity fluctuations to the temperature fluctuations. Morkovin stated that for an adiabatic wall with no streamwise pressure gradient, the total temperature fluctuations would equal to zero. Gaviglio later showed that the SRA was also valid in the presence of a streamwise pressure gradient [1]. Additionally, Crocco derived an equation, often called the Crocco integral, to relate the velocity to the temperature in both laminar and turbulent flows. He formulated an equation in the case of a weak heat flux at the wall, which is now referred to as the extended SRA solution [1, 3]. However, experiments showed that this only holds true for boundary layer flows with adiabatic walls or with a small heat flux at the wall.

Researchers have also tried to derive a *law of the wall* in a coupled turbulent boundary layer. Notably, Van Driest scaled the velocity gradient with density and extracted a transformed velocity with which the logarithmic law holds true. Following this widely accepted breakthrough, scientists extended the Van Driest transformation to characterize the velocity in the entire boundary layer [4, 5].

Despite the progress made in this field of research, a common issue frequently expressed in the literature is the difficulty in acquiring high quality time-resolved velocity and temperature data in compressible flows, especially near the walls. For this reason, it has been challenging to validate the proposed theories described above.

Research is therefore proposed with the following objectives: translate the theoretical framework previously performed using near-asymptotics [6] on an incompressible turbulent boundary layer to the realm of compressible fluid mechanics and later validate this theory with experimental testing in both supersonic and hypersonic wind tunnels. The research proposed will either support the SRA or yield a different relationship between velocity and temperature. In any case, the outcome will further the understanding of turbulent boundary layers in supersonic flows in the scientific community.

Fast-response sensors must be used to accurately measure both the velocity and the temperature fluctuations in a turbulent compressible boundary layer. For this, nano-scale anemometers developed by numerous researchers at Princeton University will be utilized: the NSTAP (nano-scale thermal anemometry probe) and the T-NSTAP (temperature nano-scale thermal anemometry probe). The NSTAP replaces hot-wires in accurately measuring velocity. The dimensions of the freestanding wire (100 nm thick, 2 μm wide and 60 μm long) allow the sensor to have an extremely high frequency response. Similarly, the T-NSTAP replaces cold-wires in measuring temperature both accurately and quickly. The cross-section of the wire filament is the same as the NSTAP, however its length is more than three times larger in order to reduce end conduction effects. Both sensors have been confirmed to have an order of magnitude higher resolution than conventional hot- and cold-wires. However, these sensors have never been tested in supersonic conditions.

After having performed initial tests in the Mach 3 tunnel and capturing interesting effects using a Schlieren imaging system, it was determined that the design of these sensors and the entire holder assembly must be modified to withstand the unsteady effects occurring during start-up of the tunnels. The ultimate objective will be to translate this investigation to a Mach 8 wind tunnel.

References:

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