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JANNAF Liquid Rocket Combustion Instability Panel Research Recommendations

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ABSTRACT

The JANNAF Liquid Rocket Combustion Instability Panel was formed in 1988, drawing its membership from industry, academia, and government experts. The panel's charter is to address the needs of near term engine development programs and to make recommendations, whose implementation will provide sufficient data and analysis capabilities to design stable and efficient engines. The panel is also chartered to make long term recommendations toward developing mechanistic analysis models that will not be limited by design geometry or operating regime. These models should accurately predict stability and minimize the amount of subscale testing for anchoring.

The panel has held workshops on Acoustic Absorbing Devices, Combustion Instability Mechanisms, Instability Test Hardware, and Combustion Instability Computational Methods. At these workshops, research projects were suggested to meet the panel's charter. Conclusions and recommendations of the JANNAF Liquid Rocket Combustion Instability Panel based on evaluation of the suggested research projects are presented.

INTRODUCTION

During the last forty years, liquid propellant rocket engine development programs have encountered combustion instability. The F-1, J-2, J-2S, OMS, LM, XLR-129, and Shuttle RCS engine development programs are examples of programs that encountered some type of instability. As recently as 1987, an engine that was expected to be stable was unstable (Ref. 1). In light of today's continuing budget issues, engine development programs cannot risk or afford an unforeseen stability problem. An unforeseen stability problem can cause program schedule slippage, cost overrun, hardware loss, or facility damage. A stability problem can constrain system performance and operating conditions to the point that the planned mission may have to be compromised. Using stability aids to solve the stability problem can add cost, weight, and complexity to the engine. In the past, development programs relied on qualitative analytical tools and full scale testing to evaluate the stability of a design. With limited resources, more economical quantitative analysis tools and subscale testing will have to be used.

Because of the many development programs during the Apollo period, the majority of combustion stability research data and analysis tools are of the 50's and 60's vintage. These data and analytical tools were very valuable in enabling the success of the programs. However, due to the limited number of development programs in the intervening period, much of the research activity was curtailed. As a result, the analysis tools failed to evolve to take advantage of the many new technologies, such as computing capabilities and advanced research diagnostics. With the limited budgets for the existing development programs, large scale engine development programs cannot afford a trial and error approach to solving combustion stability problems.

JANNAF LIQUID ROCKET COMBUSTION INSTABILITY PANEL RECOMMENDATIONS

The JANNAF Liquid Rocket Combustion Instability Panel was formed in 1988. The panel includes experts in combustion stability, representing government, industry, and academia. The panel's charter is to address the needs of near term engine development programs and to make recommendations, whose implementation, will provide sufficient data and analysis capabilities to design stable and efficient engines. The panel is also chartered to make long term recommendations with the objective of developing mechanistic analysis models that will not be limited by design geometry or operating regime. These models should accurately predict stability and minimize the amount of subscale testing for anchoring. The objective of the panel is to produce a standard model, or set of models, that will allow the rocket industry to design stable engines and make comprehensive, accurate predictions of the engine's stability. The panel intends to achieve its objective by coordinating the funding of activities through the representatives on the panel. The representives who have attended workshops are included in the Appendix. The panel decided that the objectives should be achieved through two different approaches (Ref. 2). A short term approach, with the objective of quickly upgrading and making existing stability models more usable to meet impending development programs. And, a long term approach, with the objective of addressing the issues involved in developing quantitative models.

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SHORT TERM APPROACH

Several tasks were recommended to address the short term approach. First, existing stability models should be identified and evaluated to determine their adequacy and accuracy against existing data. Second, the various models which are determined to be adequate, should be put into a modular analysis and design methodology to make them more usable. Third, the models should be evaluated to determine the required improvements.

Since the formation of the panel, many activities have been initiated to address the short term approach. The task of evaluating existing stability models to determine their adequacy and accuracy has been performed through several government contracts. Under the Oxygen/Hydrocarbon Injector Characterization contract, F04611-85-C-0100, sponsored by the Air Force Astronautics Laboratory (AL), existing models were extended. The objective of this program is to develop and demonstrate an injector design methodology capable of ensuring high combustion efficiency with stable combustion for oxygen/hydrocarbon rocket engines, based only on analysis and properly selected reduced-scale hardware testing. In the Combustion Stability Model Study, NAS 8-36274, sponsored by NASA Marshall Space Flight Center (MSFC), many of the existing models were evaluated to produce the GENeralized STAbility (GENSTA) analysis tool, which utilized a single set of existing models to perform stability analysis, and under the LOX/Hydrocarbon Rocket Engine Analytical Design Methodology Development and Validation contract, NAS 3-25556, sponsored by the NASA Lewis Research Center (LeRC), the existing models were evaluated against existing data.

The task of using the models to create a modular methodology is being addressed by LeRC in the ROCket Combustor Interactive Design (ROCCID) methodology program. ROCCID is a modular interactive methodology code that uses existing models to perform a simplified performance analysis and an in-depth stability analysis. The modularity of ROCCID allows for adding or interchanging improved models as they become available. The interactive front end of ROCCID makes it user friendly and simplifies the input procedure. The panel recommended that the ROCCID methodology should be considered as a JANNAF standard for combustion stability design and analysis (Ref. 3). To enforce this standard when it becomes available, the panel recommended that the government representatives should require the contractors to use the future JANNAF stability analysis standard in their future contracts (Ref. 3).

LONG TERM APPROACH

The panel recognized several areas of concern that must be addressed to achieve the long term objective of developing comprehensive, accurate, quantitative stability models. The panel defined five areas that affect combustion stability; (1) Injector/Feed System Dynamics, (2) Atomization, (3) Vaporization, (4) Mixing, and (5) Fluid/Wave Dynamics (Ref. 4). Atomization and vaporization were determined to be the most critical areas, because they provide the initial conditions and boundary conditions to stability analysis and, because they can cause significant changes in stability predictions (Ref. 4 and 5). The panel recommended exploring CFD techniques and improving numerical techniques to provide an increase in analysis capability (Ref. 4 and 5). They recognized that the stability data content and format is not standardly reported and that data has been lost (Ref. 2). The panel also recognized that acoustic damping device modeling capability needs improvement (Ref. 5 and 6).

Atomization. The panel concluded that atomization is the primary area where research and model improvements are required and that detailed atomization rates and drop size distributions should be obtained (Ref. 4 and 5). Because the atomization process determines the initial conditions in the combustor, obtaining an accurate prediction of drop size will benefit stability and performance analyses. Empirical correlations are the state of the art. They were developed using cold flow testing and may not be accurate for hot fire conditions. Correlations were developed under hot fire rocket conditions, but they are of limited sample size, propellant combinations, and injector type and are not used by the industry (Ref. 7 and 8). Therefore, the correlations need to be tested against realistic hot fire conditions to determine their accuracy. Often, the analyst must extrapolate these correlations because the engine is operating in a different regime. Therefore, new data must be acquired for regions where extrapolation would be required.

In addition to steady flow correlations, the panel recommended the development of unsteady cross-flow atomization models or correlations (Ref. 5). When the spray is hit by an acoustic wave in the chamber, flow visualization has shown that the atomization process is broken up and the drops are randomly scattered. The steady flow atomization correlations become highly inaccurate under these conditions, and the modelers do not know how to make corrections for these conditions. Therefore, atomization data must be acquired under cross-flow conditions.

It was also recommended that a "first principles" atomization model be developed (Ref. 4). This type of model will take the empiricism out of atomization modeling and would avoid the problems associated with extrapolation. Therefore, such a model should be capable of modeling different injector geometries using different fluids under different chamber conditions.

Vaporization. The panel recommended that advanced subcritical and supercritical droplet vaporization models should be developed (Ref. 4 and 5). In addition, an experimental program should be developed for measuring drop size, velocity, species, and temperature to validate the vaporization models. To make the measurements for atomization and vaporization, high frequency diagnostics with repetition ranges of 10^3 to

10^4 need to be developed.

Numerical Modeling. The panel concluded that CFD methods should be phased into stability modelling (Ref. 4 and 5). CFD methods can immediately be applied in several places, such as mixing, steady state combustion, and atomization stream breakup. The three phases consist of the development of a steady state CFD combustion code, a time-dependent CFD combustion response code, and an integrated CFD wave mechanics/combustion response code. The CFD experts on the panel estimated that it would take fifteen years to perform all three modelling phases. In addition, the computational techniques must be evaluated for their capability to handle high frequency oscillatory flowfields that are common in unstable rocket combustors.

Standardized Reporting Requirements and Database. The panel recommended standardizing reporting requirements (Ref. 2). Currently, an effort is proceeding to evaluate and modify the JANNAF Rocket Engine Performance Test Data Acquisition and Interpretation Manual (Ref. 10) on data reporting standards to make future data more accessible. Progress on evaluating and modifying the manual was reported, and the panel recommended that the standards should be compared to those used in the ramjet and solid rocket communities (Ref. 3).

The panel also came to the conclusion that past data are either lost or inaccessible and future modelers could not easily utilize the available data. Therefore, it was recommended that a centralized, standardized experimental stability and performance database should be established. The panel recognized that not enough fundamental data exists and recommended that data should be obtained at conditions that are representative of that in a rocket combustor.

Acoustic Damping Devices. The panel established that damping devices should only be used as a backup device when engine stability problems are suspected (Ref. 6). They estimated that cavity sound speed could be predicted to an accuracy of only 50% (Ref. 6). Since the determination of cavity sound speed is crucial for determining acoustic absorber tuning and effectiveness, the panel recommended that cavity sound speed data should be collected, and numerical modelling should be used.

Because of the limited capabilities of baffle models, it was recommended that more work should be performed in this area (Ref. 6). The interaction and feedback between the baffles and acoustic cavities should be considered, and the scope of the work should go beyond that of DIST3D (Ref. 10). Combustion distribution should be treated more rigorously than the simple linear model in DIST3D. In addition, a model for the interaction of non-sinusoidal waves with baffles, absorbers, and the nozzle should be developed (Ref. 5). The panel recommended that experiments be performed to verify the accuracy of predicting the baffle absorption constant and frequency depression (Ref. 6). Since a model does not exist for evaluating baffles that contain a hub, it was recommended that a modelling effort should be started to develop a baffle/hub model (Ref 5).

RECOMMENDED RESEARCH

Research projects were requested from the panel members to meet the general recommendations resulting from the workshops. They responded with projects regarding atomization, vaporization, CFD utilization, database, and baffle cavity modelling.

ATOMIZATION STUDIES

Many projects were proposed to study atomization. The proposed projects apply to impinging, shear coaxial, and swirl coaxial elements.

A project to perform cold flow steady-state atomization measurements of injection elements to extend the current data base was proposed. Several types of measurement techniques were suggested. They include Malvern, phase doppler, X-ray, neutron radiography, laser sheet visualization, and laser induced fluorescence measurement techniques. Using these techniques, experimental data would consist of mean drop diameters of sprays, drop size distributions, drop velocities, and jet break-up images. These data could then be correlated with element geometry and size, fluid properties, and operating conditions to provide generalized relations, and thus, allowing description of spray results for arbitrary elements and operating conditions within the ranges of variables tested.

Some work has been started in this area. Woodward, Garner, Cheung, and Kuo (Ref. 11) have begun using X-ray radiography and laser sheet visualization to study the ambient liquid jet break-up and plan to perform tests at 6.89 X 10^6 Pa (1000 psi) in the future. Zaller (Ref. 12) is obtaining injector drop sizes using phase doppler drop sizing with plans to test up to 4.13 X 10^6 Pa (600 psi) in cold flow and 5.51 X 10^6 Pa (800 psi) in hot fire conditions. Krulle, Mayer, and Schley (Ref. 13) are planning atomization cold flow tests with a pressurized chamber.

Another suggested project for atomization studies is to determine the effect of cross-flow on the break-up and atomization processes. The shattering of large drops into small drops can cause the drops to burn rapidly and sustain or amplify a pressure wave. A project to study these effects would first include surveying existing drop shattering data and correlations. The effects of sinusoidal waves, steep fronted periodic waves, and single shock waves on the atomization and break-up processes should also be studied. The magnitude and statistical variation of the resulting drop size as a function of the amplitude and frequency of the waves could be produced, and an empirical correlation would be developed. This correlation could be incorporated into existing response models. The enhanced model should be validated by comparing its predictions to existing stability test data.

Planning and designing is proceeding in this area. Jacobs and Santoro (Ref. 14) are planning to use an acoustic driver on a liquid jet and to use laser visualization to study the effect on jet break-up and atomization. Zaller (Ref. 12) is planning to use a steady cross-flow gas stream on the injection stream to determine the cross-flow effects on atomization.

A project has been suggested to obtain hot fire atomization data and compare it to cold flow test data. This project would determine whether the cold flow correlations that are used to design engines are valid under hot fire conditions. A second benefit of this project would be to determine if less expensive cold flow atomization testing can be substituted for more expensive hot fire atomization testing. Most of the existing programs to obtain these data are in the planning stages.

The results from the above projects would lead to a final project of atomization modelling. The modelling of atomization takes two forms. The first is to develop correlations from the data similar to what was done in the past. The second is to develop a CFD model of the atomization process from first principles. Chuech et. al (Ref. 15) are beginning work in using CFD methods to predict jet breakup and atomization.

VAPORIZATION STUDIES

As a result of the workshops, recommendations were made to study vaporization, and research projects have been proposed to fulfill these recommendations. These projects would generate a database on droplet vaporization under reacting and non-reacting conditions. Vaporization testing should include subcritical, near critical, and supercritical test conditions. Measurements should be made of single droplet, dilute spray, and dense spray vaporization under conditions that are representative of a rocket combustor. These measurements should be performed under steady and cross-flow conditions. The resulting data would be used to validate existing models and create new models as required.

Some work is already proceeding in this area. Yang (Ref. 16) is attempting to calculate from first principles the detailed flow structures and gas-droplet interface transport involved in high pressure droplet vaporization and combustion. Sirignano and Chiang (Ref. 17) have been developing ways to compute the vaporization of drops in gas turbines and have begun to apply this technique to rockets. Priem (Ref. 18) is proposing that the Onion Skin method of predicting supercritical drop vaporization is simple, sufficiently accurate, and not computer intensive, but he says that experiments at high Reynolds number and supercritical conditions need to be performed to validate this theory. Norton, Litchford, and Jeng (Ref. 19) are experimenting with the vaporization of a single drop. Santivicca et. al (Ref. 20) are experimentally examining the effect of droplet turbulence interaction on the vaporization process.

CFD UTILIZATION

The panel determined that CFD modelling would be a long term project of about fifteen years and that the first step of this long term project should begin now. A steady state combustion code should be developed that can handle two phase flow, multiple reactions, and compressible flow that are typical in rocket combustors.

Some work is proceeding in this area. The use of CFD methods is being attempted by some of the researchers mentioned above (Ref. 15, 16, and 17). Merkle (Ref. 21) is using CFD methods to produce a CFD rocket combustor mixing and combustion code. Liang, et. al, (Ref. 22) wrote the Advanced Rocket Injector Combustion Code (ARICC) and are trying to improve its predictive and computer run time capabilities.

DATABASE

The panel recommended that a stability database should be generated to make the data accessible and easier to use. A project was suggested to meet this recommendation. The first part of this project would be to develop a format for reporting and storing design, performance, stability, and operating characteristics for injector/engine combinations. The second part of this project would be to survey government agencies, engine contractors, and universities to provide data related to research, development, and production hardware. This database would require periodical maintenance.

BAFFLE/CAVITY MODEL

A baffle/cavity modelling project was suggested. The objective of this project would be to develop an integrated baffle/cavity model to include interactive effects of baffles and cavities and effects of distributed combustion. This new model would go beyond that of DIST3D (Ref. 10) and consider the interaction and feedback between the baffles and acoustic cavities. The model would treat combustion distribution more rigorously than the simple linear model in DIST3D. This would allow for more accurate determination of the interaction of combustion distribution and stability aid placement. In addition, hub baffles would be addressed in the model. The model would then be tested in hot fire and cold flow tests.

SUMMARY OF RECOMMENDATIONS

The panel has recommended that the fundamental mechanisms of stability and their modelling should be the main area of focus for future liquid rocket combustion stability research. The panel has determined that atomization and vaporization are the most important mechanisms that must be investigated for combustion instability modelling improvement. They also concluded that to make the modelling process more efficient, a standardized accessible stability database must be established, and they recommended that a JANNAF standardized method of analyzing stability should be adopted.

The panel feels that CFD modelling has its place in stability analysis and should be pursued over the long term. Therefore, classical wave mechanics modelling methods must be the mainstay, but CFD methods can fill niches in developing mixing, steady state combustion, and stream breakup codes. These codes would enhance the classical wave mechanics methods. The panel recommended that, because the ideal stability model does not exist, work will still have to continue on damping devices.

CONCLUDING REMARKS

Clearly, much work needs to be performed to develop models that will accurately predict stability for development engines. The panel members felt that there is an overwhelming number of issues to be addressed, but that they can be solved methodically, if a sufficient and steady level of resources are committed. Because stability is vaporization limited, atomization and vaporization processes control most of the instabilities encountered. Atomization and vaporization provide the initial and boundary conditions for stability models. Therefore, of all the recommendations provided, greater insight into atomization and vaporization is expected to provide the greatest payoff for improving stability modelling.

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APPENDIX

Liquid Rocket Combustion Instability Workshop Attendees

Mark D. Klem, Chairman	NASA Lewis Research Center
Carl Aukerman	NASA Lewis Research Center
Kevin J. Breisacher	NASA Lewis Research Center
Ken Davidian	NASA Lewis Research Center
Michelle Zaller	NASA Lewis Research Center-Sverdrup Tech.
John Hutt	NASA Marshall Space Flight Center
P. Kevin Tucker	NASA Marshall Space Flight Center
Tim Edwards	Air Force Astronautics Lab
Phillip Kessel	Air Force Astronautics Lab
Al Kudlach	Air Force Astronautics Lab
Jay Levine	Air Force Astronautics Lab
Jim Nichols	Air Force Astronautics Lab
Larry Quinn	Air Force Astronautics Lab
Lt Ken Philippart	Air Force Astronautics Lab
Lt Jim Rymarcsuk	Air Force Astronautics Lab
Elizabeth Slimak	Air Force Astronautics Lab
Mitat A. Birkan	Air Force Office of Scientific Research
Peter J. O'Rourke	Los Alamos National Laboratory
William Anderson	Aerojet Propulsion Division
Jeffery Muss	Aerojet Propulsion Division
Thong V. Nguyen	Aerojet Propulsion Division
Jerry L. Pieper	Aerojet Propulsion Division
Richard Walker	Aerojet Propulsion Division
Subra V. Sankar	Aerometrics, Inc.
Andrej Przekwas	CFD Research Corporation
Alan Hersh	Hersh Acoustical Engineering
Richard J. Priem	Priem Consultants, Inc.
James J. Fang	Rocketdyne Division
Robert J. Jensen	Rocketdyne Division
Pak Liang	Rocketdyne Division
Thomas Coultas	Schafer Associates Inc
Curtis Johnson	Software & Engineering Associates
Gary R. Nickerson	Software & Engineering Associates
Robert Glick	Talley Defense Systems
B. B. Stokes	Thiokol Corporation
James D. Sterling	TRW Corporation
Robert Carrol	United Technologies Pratt & Whitney
George B. Cox, Jr	United Technologies Pratt & Whitney
D. Lee Hill	United Technologies Pratt & Whitney
Gregory M. Dobbs	United Technologies Research Center
Donald J. Hautman	United Technologies Research Center
Thomas J. Rosfjord	United Technologies Research Center
Fred Culick	California Institute of Technology
Frederick H. Reardon	California State University - Sacramento
Bill Sirignano	University of California - Irvine
Charles Mitchell	Colorado State University
John W. Daily	University of Colorado
Charles Merkle	Penn State University
H. Robert Jacobs	Penn State University
Vigor Yang	Penn State University
Robert J. Santoro	Penn State University
San-Mou Jeng	University of Tennessee Space Institute