CRYOGENIC INDUSTRIES

FROSTBYTE

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Ecologically improving Gas and Oil Well production with Nitrogen "fracking"

Cryoquip's Advanced Diesel Fired Vaporizer (Model ADFV) has been providing high pressure nitrogen gas for injection into Natural Gas and Oil wells to enhance and stimulate well production for nearly a decade. It is subject to a continuous program of research and development to ensure the design is aligned with the fast pace changing demands on these systems, resulting in today's lighter, more efficient, compact, automatically controlled and more reliable ADFV model.

All oil and natural gas wells drilled today eventually become marginal producing wells when most of the readily available hydrocarbons have been extracted. In order to extract more oil or gas from these existing wells, some type of rejuvenation or enhancement is required to increase the flow of hydrocarbons into the well bore so that they can be easily extracted, preventing the need to drill another well. Hydrocarbons are entrained in the pore spaces in the underground formation strata which comprise sand, shale and rock. Enhancement is achieved by 'fracturing the strata', commonly known as "fracking" to release more product.

The difference between Cryoquip's ADFV *Nitrogen* fracking unit compared to the other types known as *hydraulic* fracking is that Nitrogen is 100% environmentally friendly.

No hydrocarbon mixes are used, no acid or chemicals, no polluted water, just *green inert nitrogen.*

This method of fracturing pressurizes the well with very high pressure inert Nitrogen, between 10,000 and 15,000 psig which is high enough to crack even the toughest strata. Fracturing makes new flow paths and increases the size of existing flow paths, allowing increased flow of hydrocarbons into the well, thus increasing overall production. In hard rock the pressurization with nitrogen gas creates a series of narrow cracks which serve as flow channels into the well. In softer high permeability rock pressurization creates short, wide fractures that extend short distances into the strata.

To meet the needs of the oil and gas industry, for high pressure, high flow rate Nitrogen gas, Cryoquip developed a portable, compact, independently powered, light weight, truck/trailer mounted direct fired vaporizer featuring a hydraulically driven fan, high efficiency heat transfer coil, high voltage spark ignition system, and fully automated discharge temperature controls. The Advanced Diesel Fired Vaporizer (ADFV) series was developed nearly a decade ago, to provide an environmentally friendly fracking process, and today many units are in operation and integrated on fully self contained mobile Nitrogen "gas fracking" rigs around the world.

The Advanced Diesel Fired Vaporizer Series is continuously being developed to increase individual capacities up to 2 million SCFH (53,000 Nm3/hr) of Nitrogen flow, and increase operating pressure to 20,000 psig (1380 bar) to improve performance. The vaporizer comprises a strategic arrangement of combustion chambers, capable of multi-stage automatic firing to enhance the overall range of temperature control and maximize fuel efficiency. A multi-bladed fan provides air to the vaporizer for combustion and system cooling. A unique design high voltage spark ignition system coupled with a standing pilot ensures automatic instantaneous firing. The control system ensures just the required amount of heat into a specially designed, robust vaporizer heat exchanger which efficiently absorbs the heat into the Nitrogen stream. The design minimizes overall weight and ensures compact dimensions, without compromise to overall reliability and

ACD’s strength in LNG fueling is showing

Core to LNG (Liquefied Natural Gas) fueling applications are ACD pumps. From low pressure to high pressure requirements, ACD has developed a product range that meets industry demands for land, rail and marine fueling systems. ACD’s broad product line of cryogenic pumps and fueling systems are used in over 1,200 LNG or LCNG installations worldwide. Recent contracts have been awarded to ACD in both rail and marine on-board systems further expanding the company’s reach into LNG markets.

LNG refueling, often used for buses and/or refuse trucks, is more simplistic in design compared to an LCNG station. To transfer LNG from the storage tank to the on-board vehicle tanks for buses and/or trucks, ACD’s TC-34 submerged pumps are used.

ACD’s TC-34 submerged pump (shown below) is the industry standard for LNG fueling stations and on-board ‘boost’ pump systems.

Typical pump requirements for LNG fueling facilities are:

Flow rate: *10-90 gpm (38-340 lpm)*

Differential Head: *50 – 1,600 feet (15 – 488 meters)*

Rpm range: *1,500 – 6,000*

P2K

Duty: Light – Medium (2 – 8 hours/day)
Flow Rate: up to 6.6 gpm (25 lpm)
Discharge Pressure: up to 4,700 psi (324 bar)*
Designed HP Rating: 15 – 40 hp (11-30 Kw)
Drive End: Grease Lubricated
Other Liquids Pumped: Lox, Lin, Lar

* Higher pressures available with smaller cold ends

LCNG fueling stations require both a TC-34 pump and a high pressure reciprocating pump to increase pressures up to 3,600 – 5,500 psi (250 - 379 bar). ACD offers several high pressure reciprocating pumps to meet application requirements based upon the type of station, duty required and pumping parameters.

X9 Series

Duty: Medium – Heavy Duty (6 - 18 hours/day)
Flow Rate: up to 37 gpm (140 lpm)
Discharge Pressure: up to 6,000 psi (414 bar)*
Designed HP Rating: 15 – 200 hp (11-150 Kw)
Drive End: Splash-Oil Lubricated
Other Liquids Pumped: Lox, Lin, Lar, Hydrogen

* 10,000 psi (690 bar) is available with 1.25” (32mm) cold end

SGV Series

Duty: Medium – Heavy Duty (6 - 24 hours/day)
Flow Rate: up to 37 gpm (140 lpm)
Discharge Pressure: up to 6,000 psi (414 bar)*
Designed HP Rating: 15 – 200 hp (11-150 Kw)
Drive End: Forced-Oil Lubricated
Other Liquids Pumped: Lox, Lin, Lar, Hydrogen

*10,000 psi (690 bar) is available with 1.25" (32mm) cold en

In addition to vehicle fueling, ACD's improved sealless AC-32 design is widely used for LNG bulk transfer applications in light end services. ACD currently offers six (6) sizes with flows and pressures up to 700 gpm (2,660 lpm) and 125 psi (9 bar), respectively. The pumps are designed in accordance with the NFPA (National Fire Protection Association) 79 Electrical Standards.

The AC-32 is designed for long life with zero leakage. The need for a conventional shaft seal is eliminated by integrally connecting pump and motor as a single unit design. Reliability of the sealless pump begins with an advanced motor design and system techniques to ensure liquid cooling of the motor is properly transferred throughout the pump to prolong motor life and reduce winding losses.

Other features include:
- state of the art inducers to provide the lowest possible NPSH by employing computer analysis utilizing hydraulic parameters to their highest degree
- lubricated bearings designed and manufactured to exacting specifications to operate in cryogenic fluids

These pumps are used universally in LNG off-loading and loading applications for trailers, rail tank cars, tank-to-tank transfer and recently in bunkering systems for LNG fueled ships. The sealless design, coupled with the motor and bearing configuration allow for reliable operation for an extended period of time (typically years). The benefits of the sealless pump are enhanced when submerged in a VJ sump (similar to the TC-34 installation) when no icing is visible and the system provides 'instant on' operation.

Driven by economic and environmental factors, LNG propulsion is a quickly developing technology for the shipping and rail industries. Starting with medium speed four-stroke engines using natural gas as propulsion fuel, a number of new technologies have been developed in recent years including those for two-stroke engines. One of the major innovations was the introduction of slow speed, two-stroke diesel engines using dual fuel (natural gas & diesel mixture) technology by MAN Diesel & Turbo (MAN) in 2011.

ACD's model MSP-SL Dual High Pressure Pump System will be used in TEEKAY's new 173,400 cbm ME-GI LNG carriers. The vessels will be built by DSME and will be Det Norske Veritas (DNV) classified.

ACD's reciprocating MSP-SL pumps increase low pressure (minimum 2.5 - 4.0 barg) LNG supplied from boost pumps to high pressure (350 barg) LNG. High pressure LNG is then discharged to a heat exchange system (provided by Cryoquip, Inc) which vaporizes the liquid to gas. The high pressure natural gas is then fed to the engine's high pressure fuel control valves through a manifold system designed by MAN.

For low pressure (8-10 bar), four-stroke marine engine requirements, ACD's MSP-34 submerged pumps are installed in the ship's cargo hull or the C-type LNG tank(s). Standard flow rates are 0.4 – 5.0 m^3/h using a variable frequency drive

ACD's Model MSP-34 is shown installed in an Anthony Veder, 15,600 m3 LNG cargo ship. The FGS (Fuel Gas System) was designed and installed by TGE Marine Gas Engineering.

For more information, visit ACD's LNG products website at www.acdlngpumps.com or contact Richard Young at *ryoung@acdcom.com*

Small Scale LNG

Operational flexibility is an essential design requisite for today's small scale LNG plants. LNG as transportation fuel is currently enjoying a tremendous growth potential in the U.S since it is a low-cost, clean, abundant, and domestic fuel. Many fleets of ships, trucks, and buses are converting to LNG as new engine technologies are introduced, and LNG fueling infrastructure are built to take advantage of the price "spread" between diesel and natural gas. (See Figure 1). Furthermore, LNG is also expanding into off road high horse power application in drilling rigs, remote power generation, and even locomotives. This has led to a growing network of small scale merchant LNG plants to supply this "new" LNG market. (See Figure 2)

However, the adaptation of LNG into the transportation and the off road industries will take some time as the market deals with the classic "chicken or the egg" problem. The LNG suppliers are waiting for the users to convert their engines to LNG while users are waiting for suppliers to build the LNG fueling supply infrastructure. As such, the early market entrants of LNG plant owners and operators will have to deal with uncertain and fluctuating demands during the early stage of the plant life. It is vital for small scale plant owners to have a plant with flexible operating range as well as scalability to grow with market demand to be successful.

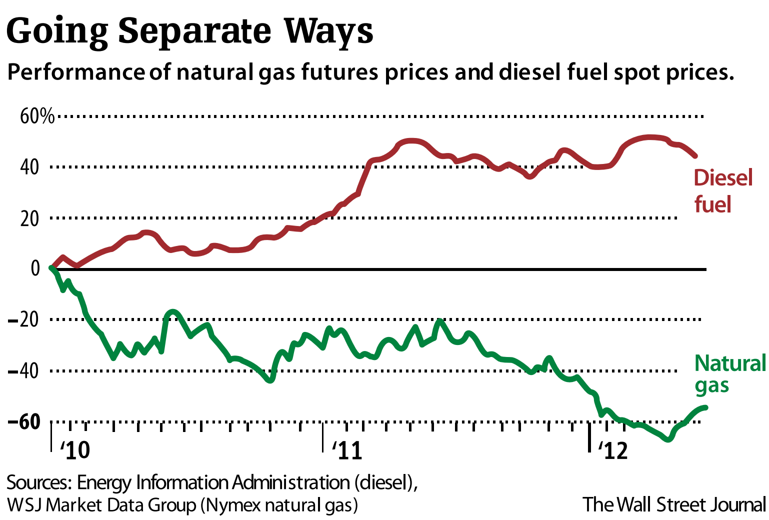

Figure 1 – Natural Gas versus Diesel Fuel Prices

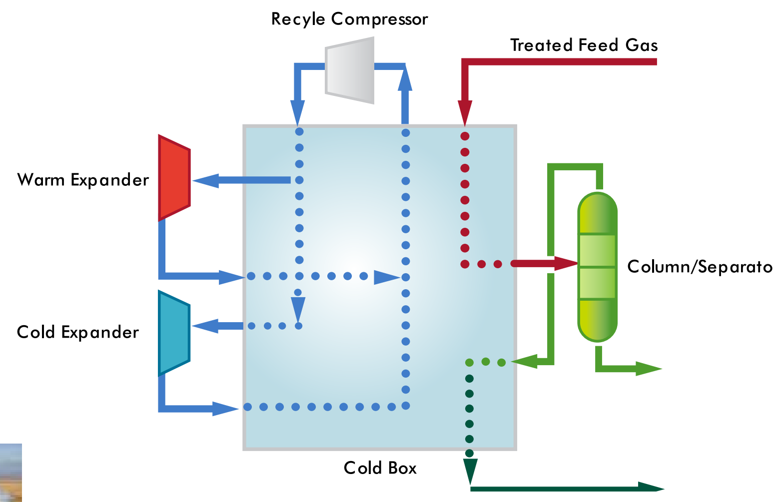

Figure 3 – Cosmodyne's Natural Gas Liquefier Nitrogen Cycle

Figure 2 – Clean Energy Fuel, Boron CA LNG Plant

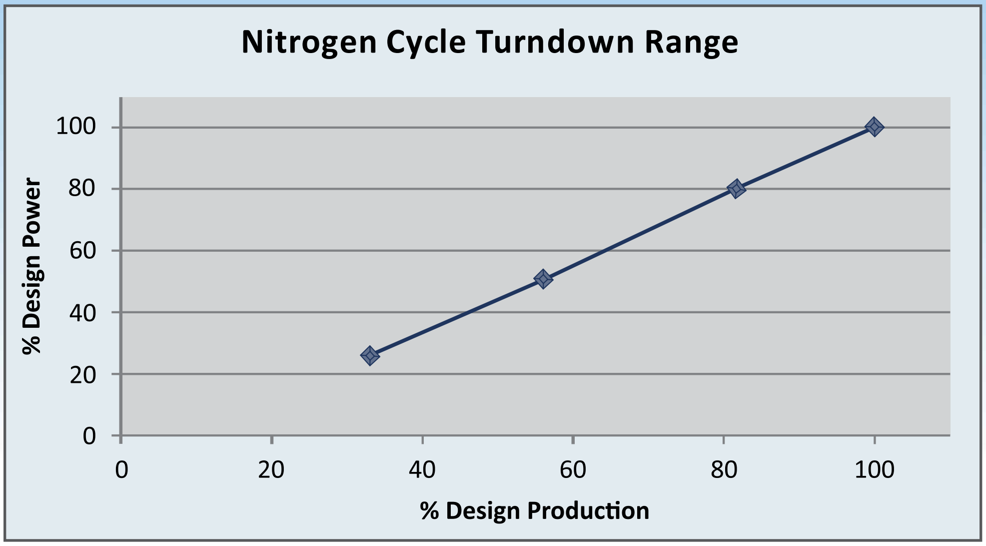

Figure 4 – Typical Cosmodyne Turndown Graph

In light of this market need, Cosmodyne improved the nitrogen expander natural gas liquefier to maximize the turndown range. Cosmodyne's nitrogen cycle LNG plant can operate down to approximately 25% of the design capacity with proportional power savings. This wide turndown range is possible since nitrogen refrigeration loop is always in a gaseous phase and can be easily manipulated to operate at reduced flows without recirculating flow through the compressors. (See Figure 3) The plant operator can vary the plant production to match the actual demand to minimize operating costs. Below is a typical turndown range for Cosmodyne's nitrogen expansion natural gas liquefier. (See Figure 4)

The wide turndown range has many benefits compared to plants that operate in "campaign mode." "Campaign mode" operation is when a plant runs at full capacity until the storage tank is filled to a set level and shuts down. The plant restarts when the storage tank runs down to a low level set point.

First, with turndown operation, the plant does not need to be turned off and on. Frequent starting and stopping of a plant can reduce reliability and plant equipment life.

Secondly, in many areas, electric utility companies adjust the electricity rates on the plant's peak load (maximum) electricity draw during a billing cycle. Hence, during the early stages of the LNG plant life where the demand is lower than the full capacity of the plant, "campaign mode" operation will result in higher electricity rates since the rate will be based on LNG plant's full capacity load. With wide turndown, the LNG plant will operate at much lower production with lower power resulting in lower electricity rate.

Lastly, many plant feed gas supply agreements have a mandatory minimum take requirement. Plants operating in "campaign mode" will be penalized since the LNG plant owner must pay the minimum gas costs even when the plant is turned off. Furthermore, even without a minimum take requirement, uncertain demand for LNG can make scheduling pipeline draws difficult and can result in unnecessary penalties for under or overestimating the amount of pipeline draw. Operating the plant at a lower capacity can make scheduling more predictable.

Cosmodyne's nitrogen cycle natural gas liquefier's wide turndown range gives the operating flexibility to deal with the unknown market demands during the early years of the LNG plant life. This new feature will allow the LNG plant operators to minimize their operating costs even when the plant is operating at lower than the full plant capacity and deal with the uncertainties of the market.

Droplet CFD

In Energent's Variable Phase Turbine [1-2] (VPT) the fluid at the inlet is liquid, flashes inside the nozzle upstream of the turbine rotor, and is two-phase inside the rotor blade passage. A previous article [3] discussed calculating the trajectories of droplets inside the turbine rotor.

In the converging section of the nozzle, the pressure decreases. When it declines to the saturation pressure, vapor bubbles form. At this pressure, the liquid is the continuous phase, the vapor the dispersed phase. With a continued decrease in pressure, eventually the liquid is the dispersed phase as droplets. The development of the dispersed phase, from the formation of vapor bubbles as the dispersed phase, the transition to liquid droplets being the dispersed phase, and the droplet breakup is not an easy task to model in computational fluid dynamics (CFD).

At first CFD is being used to investigate the flow field around droplets. An objective is to use the information gained from the calculations to develop a reduced order model that can be incorporated into traditional CFD codes and 1-D nozzle codes. Experimental work has been found for model problems to begin investigating computationally. By finding problems to study that have been investigated experimentally, the methodology used in the CFD simulations can be validated.

A starting point is to examine the flow field around a single liquid droplet. An objective is to study the breakup of the droplet. In the meantime, the breakup of a 2-D water column subjected to a shock wave is investigated, for which there is experimental data from Tohoku University [4], Japan. By considering first the breakup of a 2-D liquid column instead of a 3-D spherical droplet, the computational cost is reduced.

Initially the calculations were done by solving the Euler equations. Although the physical viscosity is ignored, numerical viscosity is still present. Figure 1 is a series of snapshots of a liquid column breaking up, displayed as a Schlieren image of the density gradient.

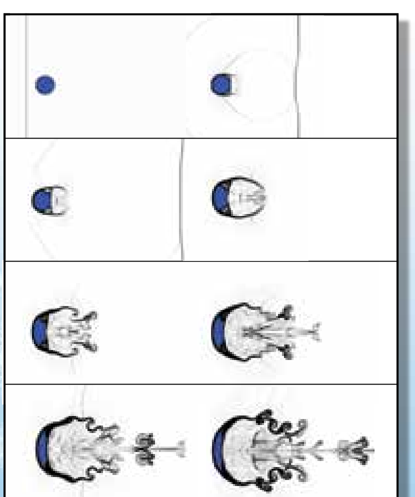

Figure 1 Schlieren images of a shock wave impinging on a liquid

The momentum interaction between the dispersed liquid phase and the continuous vapor phase is through the droplet drag, which is characterized by the drag coefficient. During the droplet breakup a question to answer is how to model the drag.

Drag coefficient

$$C_D = \frac{D}{\frac{1}{2}\rho u^2 S} = \frac{ma}{\frac{1}{2}\rho_G \; u_G - u^2 d}$$

S = frontal area of cylinder, in 2-D the diameter

The liquid cylinder's center of mass was obtained from the CFD results during the time interval while there is no mass flux through the boundaries. Its position, velocity and acceleration were calculated. Plotted in Figure 2 are drag coefficients for the incident planar shock with Mach numbers of 1.3, 1.5 and 1.7. The initial column diameter is used to non-dimensionalize the drag coefficient.

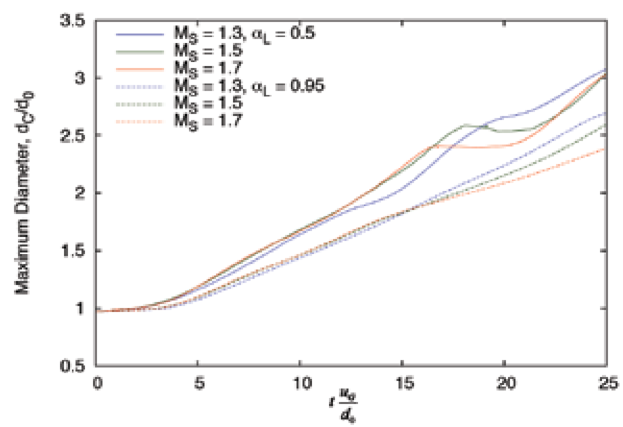

Figure 2 Drag coefficient non-dimensionalized using the initial column diameter, for several different incident Mach numbers.

From the calculation, the frontal diameter of the deforming cylinder was obtained as a function of time for different values of the liquid volume fraction threshold, Figure 3.

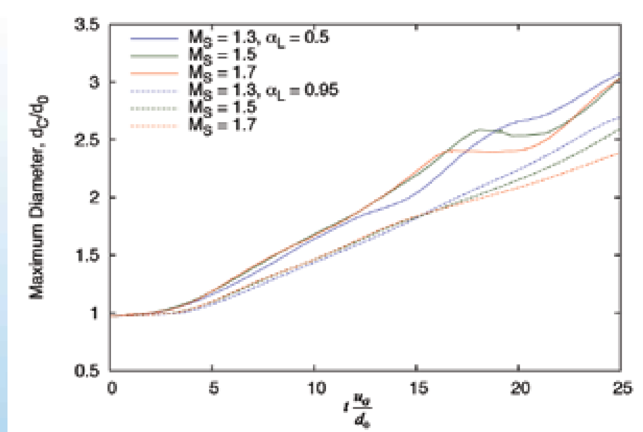

Figure 3 Frontal diameter of the deforming cylinder for two different threshold values of the liquid volume fraction, for several different incident Mach numbers.

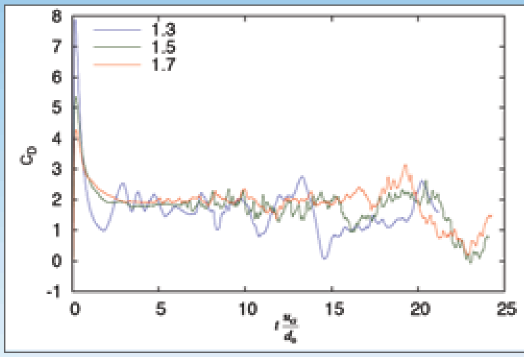

Figure 4 Drag coefficient non-dimensionalized using the deforming column frontal diameter, for a threshold value of 0.95 of the liquid volume fraction, for several different incident Mach numbers.

By using the actual column diameter instead of the initial diameter, the drag coefficient shows significantly less variation during the breakup period that is simulated, Figure 4.

In the application of interest, the droplet is not in isolation, but is part of a cloud. At Sandia National Laboratory [5], experiments have been conducted on a planar shock wave impacting a curtain of solid particles.

The simulation focuses on the early stage of the experiment when the particles have not yet moved and can be assumed to be fixed in space. The 3-D particle cloud is modeled by an array of staggered cylinders, Figure . With the stagger arrangement used, the open cross sectional area varies by less than 1.5%, Figure 6. The volume fraction is nearly constant through the curtain. For this 2-D model, the Euler equations are solved. The numerical method implicitly contains numerical viscosity.

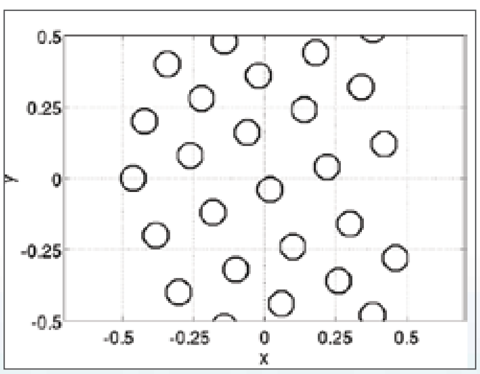

Figure 5 Array of staggered cylinders.

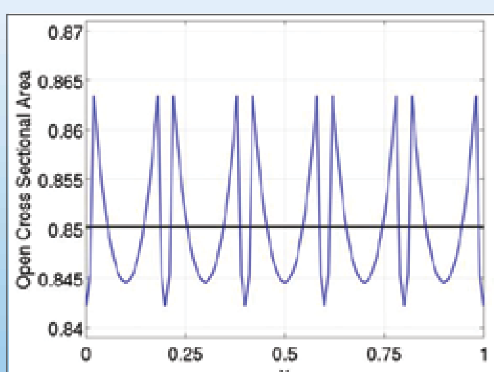

Figure 6 Open cross sectional area of the cylinder array.

Figure 7 shows the reflected and transmitted shock waves, as well as the unsteady flow conditions both inside and behind the cylinder cloud.

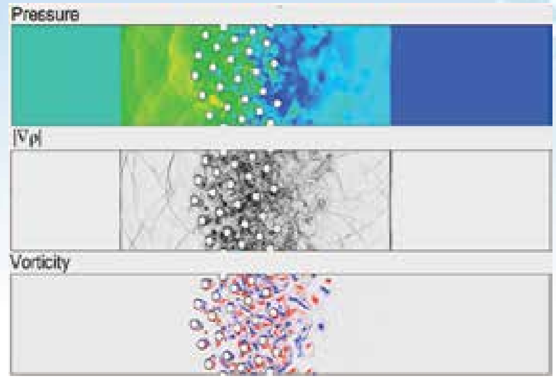

Figure 7 Flow variables of the 2-D calculation at t=3.5.

A one-dimensional model is derived from the volume-averaged Navier-Stokes equations, where the viscous stresses within the continuous phase are assumed to be negligible, but the momentum coupling terms are still considered. The 1-D model equations that were solved do not include the unclosed fluctuation terms created during the volume-averaging procedure, such as the Reynolds stress. This is a reasonable assumption in dilute multiphase flows. However, in dense flows this assumption may not be appropriate.

The miscellaneous particle forces are assumed to be included in the drag coefficient for the quasi-steady drag force on a single particle

$$F_i^{qs} = \frac{1}{2}\rho C_D A_p \,| u_i - v_i |\, (u_i - v_i)$$

where A_P is the particle cross-section, C_D is the drag coefficient, and u and v are the continuous and dispersed phase velocities, respectively. For the time period considered the particle is fixed in space, so $v_i = 0$. For the 2-D particle, the cross-section area is its diameter, D_P. The drag coefficient C_D was determined by finding the value that best matches the reflected and transmitted shock locations and magnitudes of the 2-D solution.

Figure 8 - Figure 10 compare the solution of the 1-D model with a planar average of the 2-D result at the non-dimensionalized time of 3.5. The particle curtain is located between -0.5 < x < 0.5. For the plots of density and velocity, the 2-D results appear to oscillate around the 1-D model results for a significant portion of the solution. For these profiles, two additional cases are shown where the drag coefficient is increased and decreased by 30%. Small, yet noticeable, differences can be observed in the shock locations. This suggests that the methodology used is adequate to evaluate an overall mean drag coefficient.

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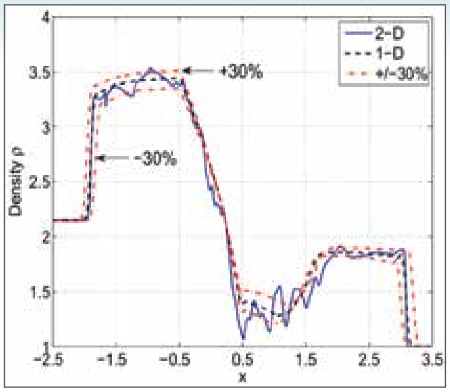

Figure 8 Comparison of the density from the 1-D model and with the planar average of the 2-D model at t=3.5. In addition for the 1-D model, the drag coefficient was varied by +/- 30%.

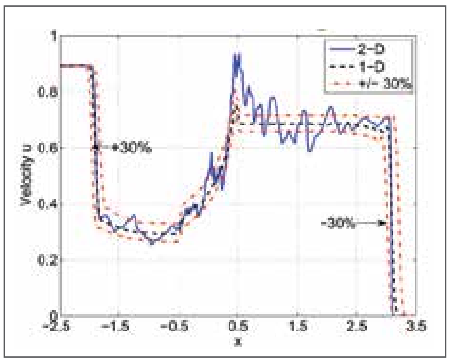

Figure 9 Comparison of the velocity from the 1-D model with the planar average of the 2-D model at t=3.5. In addition for the 1-D model, the drag coefficient was varied by +/- 30%.

In Figure 10 the planar averaged pressure in the 2-D result is consistently lower than that predicted by the 1-D model inside the particle cloud and downstream of the trailing edge until x 1.5. This is attributed to the fluctuations associated with the vortical structures (see Figure 7), which is a behavior that the 1-D model, in its current form, is incapable of reproducing. Also shown is the sum of the volume-averaged pressure $p_T = \langle p \rangle + \alpha_c \langle \rho u''u'' \rangle$

The effective total Reynolds pressure better matches the 1-D model solution inside the cloud and unsteady region. The 1-D model overestimates the static pressure by including the energy that should be contained in turbulent kinetic energy. This flow is too dense to neglect the Reynolds stress terms.

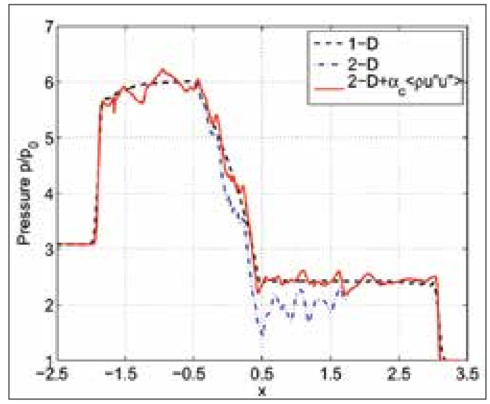

Figure 10 Comparison of the pressure from the 1-D model with the planar average of the 2-D model at t=3.5, and with the Reynolds stress term included.

By examining how 2-D and eventually 3-D computations compare with experimental data, we would have more confidence in the reduced order model that we want to develop to describe the 3-D phenomena of flow around droplets.

[1] Lance Hays, "The Energent Variable Phase Turbine expands liquids or supercritical fluids used in refrigeration," *FrostByte*, Summer 2008, pages 1, 4.

[2] Lance Hays, "Cryogenic Liquid Expanders," *FrostByte*, Summer 2011, page 2.

[3] Ron Franz, "Droplet Trajectories in a Turbine Rotor," *FrostByte*, Winter 2011, page 7.

[4] D. Igra and K. Takayama, "Experimental Investigation of Two Cylindrical Water Columns Subjected to Planar Shock Wave Loading," *Journal of Fluids Engineering*, 125: 325–331, 2003.

[5] Wagner, J. L., Beresh, S. J., Kearney, S. P., Trott, W. M., Castaneda, J. N., Pruett, B. O., Baer, M. R., "A multiphase shock tube for shock wave interactions with dense particle fields," *Experiments in Fluids* 52 (6), 1507–1517, Feb. 2012.

CRYOGENIC INDUSTRIES

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CRYOGENIC INDUSTRIES TO RELOCATE HEADQUARTERS

This Fall Cryogenic Industries will relocate its headquarters offices from Murrieta, CA to Temecula, CA. The new facilities will house administrative, finance, treasury, legal, internal audit, regulatory compliance, human resources and tax functions. An announcement with the new address and telephone numbers will be made at the time of the relocation.

North America

ACD • Atlanta • California • Houston • Pittsburgh • Red Deer • Toronto
Cosmodyne • Cryoquip • Energent

South America

ACD • Cryoquip

Australia

Cryoquip

South Africa

Cosmodyne • Durban

Europe

ACD Cryo • Cryoquip

Middle East

United Arab Emirates, Dubai

Asia

ACD • China • Korea • Malaysia • India
Cryoquip • China • Malaysia • India
Rhine Engineering • India