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# Characterization of the Fluid Deaeration Device for a Hydraulic Hybrid Vehicle System

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## ABSTRACT

The attractiveness of the hydraulic hybrid concept stems from the high power density and efficiency of the pump/motors and the accumulator. This is particularly advantageous in applications to heavy vehicles, as high mass translates into high rates of energy flows through the system. Using dry case hydraulic pumps further improves the energy conversion in the system, as they have 1-4% better efficiency than traditional wet-case pumps. However, evacuation of fluid from the case introduces air bubbles and it becomes imperative to address the deaeration problems. This research develops a bubble elimination efficiency testing apparatus (BEETA) to establish quantitative results characterizing bubble removal from hydraulic fluid in a cyclone deaeration device. The BEETA system mixes the oil and air according to predetermined ratio, passes the mixture through a cyclone deaeration device, and then measures the concentration of air in the exiting fluid. Test results indicate the ability of the cyclone deaeration device to remove large bubbles with near 100% efficiency, while elimination of small (less than 1 mm diameter) bubbles proved to be a challenge. The explanation is provided through application of Stokes Law that shows a strong relationship between bubble size and bubble rise velocity. The theoretical analysis provides clear guidance regarding pathways towards improving the effectiveness of removing small bubbles.

## INTRODUCTION

Hydraulic hybrid vehicles use hydraulics as a means of energy storage and energy conversion for propulsion. Hydraulic hybrid concept is particularly attractive when applied to heavy vehicles due the high power density of components and an overall high efficiency of the energy conversion and storage process [1,2,3,4]. The high power density and efficient accumulator charging-discharging allows for high-energy recovery from braking (up to 70%) and allows the engine to operate more efficiently [2,5]. This is advantageous when compared to the hybrid system with an electric battery applied to a heavy vehicle, since solutions that meet both high rates and frequencies of charging-discharging an electric battery have yet to be demonstrated [1,6]. The ultracapacitor is an interesting alternative, but the technology is still under development and the cost is a significant challenge at the moment.

Hydraulic hybrid vehicle efficiency can be improved by using a dry case variable displacement piston pump as opposed to a more traditional wet case design. A wet case pump contains low-pressure oil on the backside of the pistons while a dry case pump contains gas. The oil in the wet case provides ample cooling of the pistons while a dry case system must rely on a more sophisticated cooling system. The benefit of the dry case is that higher operating efficiency can be obtained because of the reduced drag. Recent testing at the U.S. Environmental Protection Agency (EPA) showed a 1-4% efficiency improvement using a dry case pump over a wet case pump [5].

The difficulty in using a dry case pump in a hydraulic hybrid vehicle stems from oil leaks around the pistons and its presence on the gas-filled side of the pump. This oil becomes aerated by the piston movement. Some of the oil helps to lubricate and cool the pump, but it must be eventually returned to the main line of the system. Before this oil can be returned to the main line, the oil must be deaerated because gas bubbles in hydraulic oil cause low efficiency, surface erosion, oil deterioration, noise generation, and oil temperature rise [7,8].

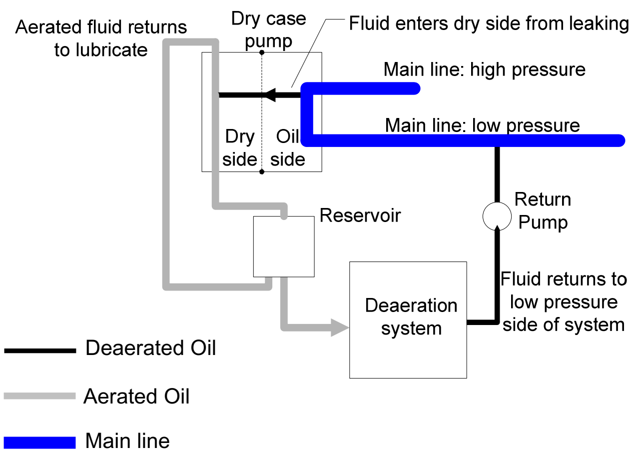



**Figure 1: Fluid Diagram for a Dry Case Pump with Deaeration System**

The flow diagram for a dry case pump with a deaeration system is given in Figure 1. The hydraulic oil enters the dry side of the pump from the main line. This oil then becomes aerated and must pass through a deaeration system before it can return to the low-pressure side of the main line.

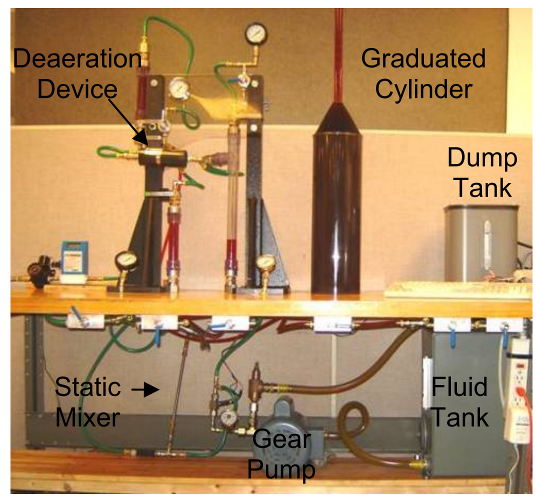
Deaeration can be accomplished using large settling tanks, membrane systems, and cyclone deaeration devices. Settling tanks are large hydraulic reservoirs where bubbles are allowed to exit out via buoyancy when given sufficient residence time [9,10]. Size constraints on a hydraulic hybrid vehicle make this option infeasible. Membrane deaeration works by using a gas-permeable / liquid-impermeable membrane and a pressure difference to separate out the gas [11]. Little research exists on membrane deaeration for a viscous fluid. Cyclone deaeration works by creating a rotating flow of incoming oil-gas mixture, which via centrifugal force separates the oil from the gas allowing the gas to be vented and the oil to continue [12]. Key advantages of cyclone deaeration are the small volume and light weight. Suzuki et al. [9,13] explored cyclone deaeration through modeling and experimentation. Yamaguchi et al. [14,15,16] studied the motions of bubbles in a rotating pipe and broadly stated that cyclone deaerators have difficulty removing small bubbles in viscous fluid. However, the research to quantify the efficiency for cyclone deaeration devices is lacking and is the goal of this research.

For a cyclone deaeration device to successfully fulfill its role in a dry case pump system it must be able to eliminate close to 100% of the gas in the oil. A bubble elimination efficiency testing apparatus (BEETA) is developed to quantitatively assess the effectiveness of a candidate cyclone device. The body of the paper begins with the description of the BEETA system design and experimental methodology. The results of testing the cyclone bubble elimination efficiency are presented next, followed by the discussion of lessons learned. The paper ends with conclusions.

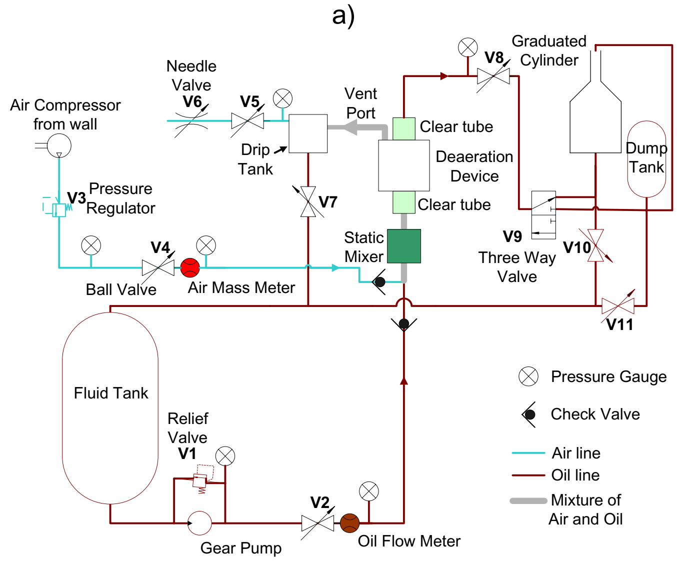
## BEETA SYSTEM

A picture and fluid diagram of the BEETA system is shown in Figure 2. The system creates a quantitatively adjustable concentration of gas in the hydraulic oil. This mixture of oil and air passes through a cyclone deaeration device, and then into a graduated cylinder to measure the outgoing concentration of air in oil. The incoming and outgoing concentrations of air in oil allow for the calculation of bubble elimination efficiency. Flow rates and pressures are controlled using a total of 11 valves (labeled V1-V11). The purposes of the valves are described in Table 1.

A gear pump flows oil from the fluid tank, which is open to atmosphere. The pressure and flow rate of the oil is controlled by a combination of relief valve V1 and a ball valve V2. These valves can be adjusted accordingly with the aid of the pressure gauges. The flow rate of the hydraulic oil is measured by a turbine flow meter (Flow Technology, Model 27-94057-110). The oil then passes through a check valve where it meets with incoming air.




a)




b)

**Figure 2: Bubble elimination efficiency testing apparatus: a) photograph of the setup, and b) a schematic of the apparatus.**

**Table 1: Valve Description**

| Valve Number | Purpose |
|---|---|
| V1 and V2 | Regulates oil pressure and flow rate |
| V3 and V4 | Regulates air pressure and flow rate |
| V5 | Controls air vent flow |
| V6 | Allows for fine tuning of air vent flow |
| V7 | Controls the amount of vent oil flow |
| V8 | Controls back pressure |
| V9 | Three way valve: Sends hydraulic fluid to graduated cylinder or dump tank |
| V10 and V11 | Allows oil to go back into fluid tank |

Air from an internal compressed air source passes through the pressure regulator V3 and ball valve V4. Similar to the oil flow, these two control devices allow for the control of both the pressure and flow rate of the air, therefore enabling adjustment of air concentration in the mixture. Pressure gauges in the system allow the operator to adjust the control devices accordingly. The mass flow rate of the air is measured by a mass meter (Omega, Model FMA-A2310).

The oil line intersects with the air line and they mix together with the help of a static mixer (Koflow, Model 3/8-21), as shown in Figure 3a. Figure 3a shows the static mixing element that goes inside the tube on the left. The mixture passes through a section of clear piping before entering and after leaving the deaeration device to aid visual observation of the oil/air mixture. The vent port of the deaeration device goes into a small drip tank where vented air and oil are separated. The vent pressure is controlled by valves V5, V6, and V7. Ball valve V5 and needle valve V6 control the amount of vent air flow and ball valve V7 controls the amount of vent oil flow. The outlet flow and pressure (back pressure on deaeration device) is controlled by V8 with the aid of a pressure gauge. The deaeration device, drip tank, clear tubes, and several valves and gauges are supported by a bracket system shown in Figure 3b.

The hydraulic fluid then continues to the three way ball valve, V9, where it goes to either the dump tank or the graduated cylinder, as shown in Figure 3c, which measures the air concentration in the fluid exiting the deaeration device. Before the test is ready to begin and while all the valves are being adjusted, the air-oil mixture flows into the dump tank. Upon beginning the experiment, valve V9 is turned allowing the mixture to pass into the graduated cylinder for measurement. The amount of air is determined after the oil in the graduated cylinder is allowed to settle for 24 hours.

The system is set up so that at the end of the testing the hydraulic fluid can be drained back into the fluid tank by using ball valves V10 and V11. The drainage comes from gravity pulling the hydraulic fluid down. The fluid tank was placed at a lower height than the graduated cylinder and the dump tank.


a) b) c)

**Figure 3: Pictures of the (a) static mixer, (b) bracket mounted cyclone deaeration device and other components, and (c) graduated cylinder**

## METHODOLOGY

An Opus Systems BM-6 cyclone deaeration device was tested in this study. The back pressure was held at a constant 138 kPa, which is specified by the vendor as the most efficient setting for air removal at any condition [17]. The difference between the vent pressure and the back pressure is defined as $P_{delta}$.

Measuring equipment and data acquisition equipment allowed for the incoming concentration of gas in the oil ($C_{in}$) to be measured. The DC voltage signals from the hydraulic oil and air flow meters were measured using data acquisition equipment (National Instrument, AT-MIO-16E-10). A Matlab program was developed to analyze this data and calculate the incoming concentration of air in oil.

The outgoing concentration of gas in oil ($C_{out}$) is measured using a large clear graduated cylinder as shown in Figure 3c. The oil-air mixture that exits the deaeration device flows into the bottom of the graduated cylinder and fills until level A, as shown in Figure 3c, is reached. After allowing 24 hours to settle the change in volume ($\Delta V$) is read, and this change in volume yields the amount of bubbles that were in the fluid exiting the deaeration device.

The gas removal efficiency ($B_{rem}$) of the deaeration device is calculated using the following equation:

$$B_{rem} = \frac{C_{in} - C_{out}}{C_{in}} \quad (1)$$

## CYCLONE DEAERATION DEVICE TEST RESULTS

The cyclone bubble elimination test were performed using the BEETA system over a wide rage of incoming oil flow rates ($Q_{in\_oil}$), range of differences in vent and back pressures ($P_{delta}$), and a range of incoming air concentrations. The hydraulic fluid was at an ambient temperature of 23°C.

For the BEETA system bubble size varies as a function of $Q_{in\_oil}$ because this affects both incoming fluid pressure and static mixer performance. Low $Q_{in\_oil}$ values create low incoming fluid pressures and poor static mixer performance which both lead to the creation of larger bubbles. $Q_{in\_oil}$ is our only measured value that relates to bubble size because incoming fluid pressure and static mixer performance were not measured.

A significant increase in bubble size was observed to occur between 3.47 L/min and 3.27 L/min, as shown in Figure 4. Through experimentation it was visually determined that for flow rates greater than 3.47 L/min the BEETA system produced bubbles of less than 1 mm diameter, hereon called "small bubbles". Similarly it was visually determined that flow rates of less than 3.27 L/min produce bubbles substantially greater than 1 mm diameter, hereon called "large bubbles".

Broad ranges of operating conditions were defined for two sets of experimentation. The first set of tests, Table 2, focused on small bubbles (smaller than 1 mm diameter). $P_{delta}$ varied between 0 and 37.9 kPa while $Q_{in\_oil}$ varied over the range of 6.15 to 3.47 L/min. The $C_{in}$ values varied between 10.5% and 42.8%. The second set of tests, Table 3, focused on larger bubbles (greater than 1 mm diameter). $P_{delta}$ varied between 13.8 and 48.3 kPa, and $Q_{in\_oil}$ varied from 3.27 to 1.47 L/min. For this set of tests, $C_{in}$ varies between 9.4% and 31.0%.

**Table 2: 1st Set of Experiments, Small Bubbles**

| $Q_{in\_oil}$ (L/min) | $P_{delta}$ (kPa) | $C_{in}$ |
|---|---|---|
| 6.15 | 13.8 | 10.5% |
| 4.67 | 13.8 | 38.2% |
| 4.65 | 27.6 | 21.3% |
| 4.62 | 0.0 | 37.8% |
| 4.44 | 37.9 | 42.8% |
| 3.72 | 0.0 | 10.2% |
| 3.47 | 27.6 | 42.0% |

The tests results in Figure 4 reveal very high efficiency of removing large bubbles, generally higher than 98%. However, the cyclone bubble elimination efficiency drops significantly as the bubble size decreases. The optimum running efficiency for this device provided by the vendor was 6 L/min [17]. As can be seen by Figure 4, the small bubble size had a greater effect than the optimum flow efficiency.

**Table 3: 2nd Set of Experiments, Large Bubbles**

| $Q_{in\_oil}$ (L/min) | $P_{delta}$ (kPa) | $C_{in}$ |
|---|---|---|
| 3.27 | 27.6 | 10.1% |
| 3.11 | 13.8 | 31.0% |
| 2.81 | 41.4 | 9.4% |
| 2.06 | 41.4 | 12.5% |
| 1.80 | 34.5 | 10.2% |
| 1.70 | 48.3 | 15.0% |
| 1.66 | 41.4 | 16.0% |
| 1.66 | 48.3 | 19.3% |
| 1.55 | 31.0 | 16.6% |
| 1.52 | 20.7 | 17.7% |
| 1.47 | 17.2 | 18.3% |

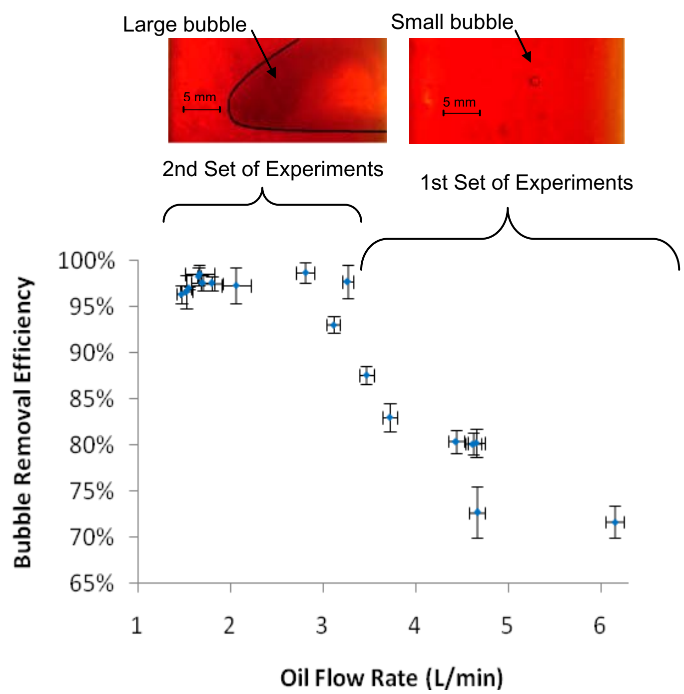



**Figure 4: Bubble Removal Efficiency for varying bubble sizes and flow rates**

Bubbles created at a $Q_{in\_oil}$ of less than 3.3 L/min are small bubbles. The observed average bubble diameter is about 1 mm. The BEETA system creates smaller bubbles at higher flow rates because of higher pressures involved and an increased mixing ability by the static mixer.

It is observed that a decrease in bubble radius lead to lower deaeration efficiency. Small bubbles (less than 1 mm diameter) are significantly more difficult to remove from a mixture than large bubbles (greater than 1 mm diameter).

## DISCUSSION

The testing results revealed significantly lower performance for the removal of small bubbles. This is explained in this section by looking at the combining effects of drag force and buoyancy force. The effects of temperature and pressure are also explored.

STOKES LAW

The bubble removal efficiency is directly correlated to terminal bubble rise velocity ($V_{rise}$). The faster bubbles ascend in the fluid (higher $V_{rise}$) the greater the probability that bubbles will exit the fluid (higher $B_{rem}$).

By combining the drag force and the buoyancy force, Stokes Law can be formed to estimate $V_{rise}$ based on acceleration force ($g$), bubble radius ($r$), and kinematic fluid viscosity ($\nu$).

$$V_{rise} = \frac{2gr^2}{9\nu} \tag{2}$$

This equation is accurate as long as the bubble remains small enough to hold its shape as it rises slowly under small Reynolds number. Since small bubbles less than 1 mm diameter are the focus of our efforts this equation is valid for our purposes.

The cyclone deaeration device relies on increasing the acceleration force, $g$, in order to increase $V_{rise}$ and therefore more quickly deaerate the mixture. As shown in Equation (2) this deaeration process becomes hindered when bubbles are small and the viscosity is high. The strong correlation to bubble size is shown in Equation (2) by the bubble radius being squared, and this enforces our experimental findings. Further analysis in the next section offers guidance regarding possible practical ways of improving bubble removal efficiency.

EFFECTS OF PRESSURE AND TEMPERATURE

Pressure and temperature affect $V_{rise}$, which in turn affects $B_{rem}$. The Ideal gas law:

$$PV = mR_sT \tag{3}$$

shows that pressure ($P$) and temperature ($T$) directly relate to the volume ($V = 4\pi r^3/3$) of a bubble of a given mass ($m$) where $R_s$ is the gas constant. $V$ relates to Stokes Law by the relationship of a spherical bubbles volume to its radius. By substituting Equation (3) to Equation (2) and adding the temperature dependence of viscosity, under the exponential model, $\nu(T) = Ae^{-bT}$ with $A$ and $b$ are constants, Equation (2) can be rewritten as:

$$V_{rise} = \frac{2g}{9\left(Ae^{-bT}\right)}\left(\frac{3mR_sT}{4P\pi}\right)^{\frac{2}{3}} \tag{4}$$

This equation reveals the theoretical relationship between the temperature, pressure, and the $V_{rise}$ which in turn is proportional to $B_{rem}$. An increase of temperature leads to lower oil viscosity (less drag) and larger bubble volume (greater buoyancy force) and has a strong effect on $V_{rise}$. Decreasing the pressure has a positive effect in that the bubble occupies a larger volume and therefore creates a greater buoyant force. Future testing will focus on studying the relationships presented by Equation (4) and developing practical methodologies for improving the $V_{rise}$.

## CONCLUSIONS

The application of a dry-case hydraulic pump can be advantageous for overall efficiency of the hydraulic hybrid propulsion system. However, evacuation of fluid from the case introduces air bubbles and it becomes imperative to address the deaeration problems. The bubble elimination efficiency testing apparatus was developed to determine the bubble removal efficiency of the cyclone deaeration device. It provided the ability to adjust the bubble concentration and average size in the oil stream, and it was able to provide quantitative insight into bubble elimination process.

Experimental results reveal that bubble size plays a significant role in deaeration efficiency. Bubbles greater than 1 mm diameter could be removed with nearly 100% efficiency. However, in the case of smaller bubbles (less than 1 mm), the deaeration efficiency decreased to less than 90%. This is not acceptable for dry case pump air removal on a hydraulic hybrid vehicle because of the numerous detrimental effects air bubbles create as mentioned earlier; hence a theoretical analysis was pursued to explore possibilities for improving the efficiency of a cyclone device. The pressure and temperature of a mixture were shown to have a major impact on the bubble rise velocity. Therefore, the alternative options, including settling tank designs and vacuum air removal systems, offer promise for future improvements.

## ACKNOWLEDGMENTS

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## REFERENCES

1. R. Kepner. (2002) “Hydraulic Power Assist – A Demonstration of Hydraulic Hybrid Vehicle Regenerative Braking in a Road Vehicle Application”. SAE paper 2002-01-3128.
2. Wu, B., Lin, C.-C., Filipi, Z., Peng H., Assanis, D., “Optimal Power Management for a Hydraulic Hybrid Delivery Truck”, Journal of Vehicle System Dynamics, Vol. 42, Nos. 1-2, 2004, pp. 23-40.
3. Filipi, Z., Loucas, L., Daran, B., Lin, C-C., Yildir, U., Wu, B., Kokkolaras, M., Assanis, D., Peng, H., Papalambros, P., Stein, J., Szkubiel, D., Chapp, R.,”Combined Optimization of Design and Power Management of the Hydraulic Hybrid Propulsion System for the 6x6 Medium Truck”, International

Journal of Heavy Vehicle Systems, Vol. 11, Nos. 3/4, 2004, pp. 371-401.

4. Kim, Y. J., Filipi, Z., “Series Hydraulic Hybrid Propulsion for a Light Truck– Optimizing the Thermostatic Power Management”, SAE paper 2007-24-0080, to be presented at the 8th International Conference on Engines for Automobile, Naples, Italy, September 2007.

5. “Progress Report on Clean and Efficient Automotive Technologies Under Development at the EPA”. Advanced Technology Division Office of Transportation and Air Quality U.S. Environmental Protection Agency. January 2004.

6. R. Apter and M. Prathaler. (2002) “Regeneration of Power in Hybrid Vehicles”. IEEE.

7. W. Phillips. (2006) “The High-Temperature Degradation of Hydraulic Oils and Fluids”. Journal of Synthetic Lubrication Vol. 23, I1, pp. 39-70.

8. G. Totten, L. Canale, and H. Liang. (2005) “Hydraulic Cavitation from a Sonomaterials Science Perspective: A Review”. SAE paper 2005-01-4173.

9. R. Suzuki, Y. Tanaka, K. Arai, and S. Yokota. (1998) “Bubble Elimination in Oil for Fluid Power Systems”. SAE paper 982037.

10. C. Morgan, J. Cummings, and R. Fewkes. (2004) “A New Method of Measuring Aeration and Deaeration of Fluids”. SAE paper 2004-01-2914.

11. C. Knuppel, K. Brodt, J. Resemann, and G. Tan. (2001) “Development of Membrane Based Gas Trap”. SAE paper 2001-01-2294.

12. “Bubb-Less”. G.E. Totten & Associates. G.E. Totten & Associates. 1 Jun. 2006

13. R. Suzuki and Y. Tanaka. (2002) “Solution of Air Entrainment for Fluid Power Systems”. SAE paper 2002-01-1387.

14. H. Yamaguchi, D. Matsubara, and S. Shuchi. (2001) “Flow Characteristics and Micro-Bubbles Behavior in a Rotating Pipe Section with an Abrupt Enlargement”. IMechE.

15. H. Yamaguchi and Y. Kibayashi. (1999) “Numerical Prediction of Dispersed Bubble flow in a Rotating Pipe Section”. 2nd International Symposium of Computational Technologies for Fluid/Thermal/Chemical systems with Industrial Applications. Boston, Massachusetts. PVP-Vol. 397-1, pp. 165-172

16. H. Yamaguchi, Y. Kibayashi, and D. Matsubara. (2001) “Behavior of Dispersed Micro-Bubbles in a Rotating Pipe Section”. Journal of Mechanical Engineering Science. 215(C10), 1223-1237.

17. Roland Bishop. GE-Totten Fluid Specialist. Telephone Interview. 6 Jun. 2006.