UC Berkeley

Consortium on Deburring and Edge Finishing

Title

Investigation of Internal Cleaning Effects in Two-Phase Gas-Liquid Flows

Permalink

https://escholarship.org/uc/item/661599t7

Authors

Garg, Saurabh
Dornfeld, David
Klaus Berger

Publication Date

2009-06-25

Cleanability of Mechanical Components

David Dornfeld (PI)
Professor, Mechanical Engineering Department, UC Berkeley

Saurabh Garg
Graduate Student, Mechanical Engineering, UC Berkeley

Klaus Berger
Manager, Material Technology and Surface Treatment, Daimler AG

Abstract: In the past few years, cleanability of mechanical components became a new engineering constraint in the automotive and aerospace industry due to a rapid increase in the complexity of engines, transmissions, suspension components, etc. Cleaning processes currently used in industry are quite inefficient as they incur significant energy and consumable costs and, in many cases, cannot achieve the degree of cleanliness necessary to meet performance and service life requirements of the components. There is a good amount of scope to improve the existing technology with analytical and computational tools that can help predict and control cleaning effect at design and process planning stages. On the other hand, an improvement in the understanding of the mechanics of chip cleanability which involves interactions between the cleaning fluid and the chip critical and workpiece bottleneck dimensions can help us investigate the development of new technologies that enhance the phenomenon that aid in the cleanability of these solid particle contaminants. This work discusses the potential of using a two-phase air-water mixture for the internal cleaning of complex automotive components like the cylinder heads of internal combustion engines, by selectively exploiting specific properties of the mixture, different from its individual components.

Keywords

Design for Cleanability, Two-phase mixture, Compressibility, Void Fraction, Air Pulsing

1. Introduction

1.1 Motivation and Background: The occurrence of failure of high performance mechanical components due to hard particle contamination has increased considerably in the recent past with increasing miniaturization in order to accommodate multiple functional requirements within the same component with tighter dimensional tolerances. The increasing complexity in geometry and precision of parts also makes it harder to access all their internal surfaces thereby posing a significant challenge for their cleaning. This in turn raises the costs involved in the cleaning process from the point of view of resource consumption including initial investment, usage of consumables and energy expenses. The energy consumed and waste generated due to cleaning often comprises the bulk of the environmental impact of manufacturing these components. Thus reduction of cleaning can help reduce the lead times of part manufacturing in a production environment, save significant total costs of manufacturing, and lower the environmental impact associated with the use of energy and consumables.

The degree of cleanliness of the manufactured components has become a quality metric in itself owing to the importance of this process. The traditional approach of addressing the problem at the cleaning stage exclusively, offers limited flexibility and fewer opportunities to obtain optimal solutions to the contamination control problem in high volume, automated production systems. Measures should be taken as early in the product development process as possible to reliably achieve the required cleanliness of the components with an emphasis on reduction of costs and energy consumption. In this context, cleanability is defined as the ability to meet a cleanliness requirement, encompassing the metrics of both cleanliness and cleaning costs.

Important work on burr formation and minimization (size, location, shape, etc.) has been done by Dornfeld [1] and co-workers. In the realm of cleanability and chip optimization, Reich-Weiser and Dornfeld [2] presented an experimental investigation of the influence of machining parameters on chip geometry for enhanced cleanability. In their work, process parameters such as feed-rate, spindle speed, depth of cut, and tool lubrication have been correlated with chip geometry and size for milling and drilling processes. Avila [3] performed a black box experimental approach of testing the cleanability of different chip geometries using the Impulse cleaning Machine. He found that chip form selectively affects the cleanability of different chip types. Arbelaez et al. [4] developed tools and techniques ranging from exploring new experimental methods for quantifying parameter effects on flat plate cleaning; a macro scale optimization and visualization module for waterjet cleaning; a particle dynamics model to simulate the local scale effect of a waterjet striking a surface; and a water flow simulation module to predict cleaning incompatible features of workpieces. Garg et al. [5] formulated the mechanics for chip cleanability based on fluid transport. They developed a chip optimization model based on various factors like the effect of lift and drag forces, chip projected surface area and the orientation, on the cleanability of chips.

It can thus be seen that much of the research in contaminant cleaning has been focused on the development of analytical and computational tools and techniques for improvement of existing technologies. This work seeks to show that the limitations in current technologies can be used to build the platform for proposing the technology that will be the driver behind the development of a next generation of cleaning machines.

1.2 Limitations of existing cleaning technologies: The selection of the cleaning process, fluid media and the process parameters is ideally governed by the workpiece material properties, manufacturing method employed and the nature of contaminants involved.

Most common mechanical methods of component cleaning currently employed in automotive industry are based on the impingement of high pressure water jets on the surfaces of these components. This water jet often fails to access the internal bottleneck areas of these components with the same high pressure as the inlet value. Consequently the contaminants in these areas do not experience the amount of force necessary for their removal. The second major limitation of high pressure water jets arises out of the fact that only the initial impact of a water jet on a surface creates a sudden hammer impulse, given by equation 1:

$$P = \rho v c \qquad (1)$$

where P is the pressure, ρ is the liquid density, c is the sonic velocity in the liquid and v is the impact velocity. This initial high pressure decays very rapidly as the stream becomes continuous as shown in figure 1, probably due to the subsequent lateral jetting [6]. This continuous pressure due to a steady state impingement is given by the stagnation pressure of water in equation 2:

$$P = \frac{1}{2} \rho V^2 \qquad (2)$$

This implies that the industrial high pressure water jet operates at the base pressure of the fluid stream for most parts of the cleaning process. Over the years, industry has been increasing this base fluid pressure, thus requiring an ever increasing pumping power and associated costs for increased energy consumption.
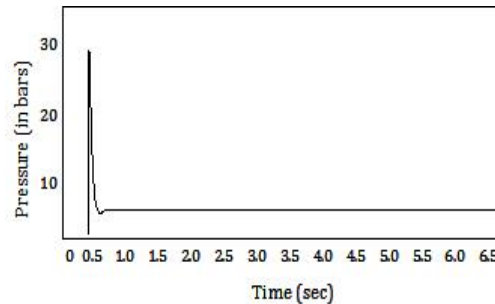

Fig. 1 A sample image for initial pressure surge during the impingement of a high pressure water jet

To overcome this limitation, Daimler developed the impulse cleaning machine that seeks to utilize the initial impulse hammer of water repeatedly in small bursts as shown in figure 2 [7]. The idea then is to disrupt the continuous flow of water with the help of valves. Figure 3 shows a schematic representation of the traveling leading edge of a water column whose momentum is suddenly arrested as it approaches the downstream valve which is closed in a few milliseconds. The leading edge of water as opposed to a metal column does not come to rest instantaneously and neither does it restitute back [8]. Because of the slight compressibility of water, the trailing edge continues to push into the trapped water column, even as the upstream valve is being closed. When flow ceases, the kinetic energy of water and that due to compression is transformed into pressure and energy is conserved. The pressure is generated in the form of a shock wave that is allowed to propagate further into the pipe once the downstream valve opens again.
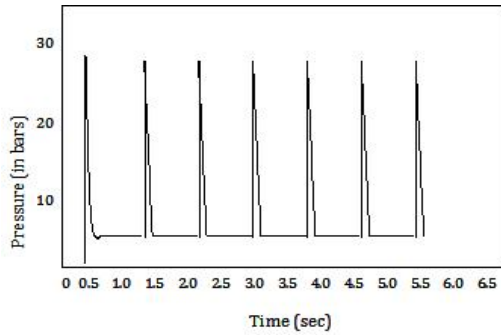
Fig. 2 A sample image for pressure variation during impulse cleaning (numbers not to scale)
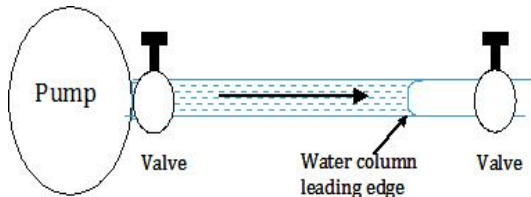

Fig. 3 A schematic diagram explaining water-hammer effect

The problem is that the water hammer effect is damaging for the valves due to high repetitive stress loading (fatigue failure) when the machine is used on an industrial scale. The momentum of water can also be arrested to some extent by a sudden decrease in the cross section of a pipe or by a pipe bend, and at the high pressures and flow rates of the base water stream used for industrial cleaning, the water hammer generated due to these effects can also damage the piping systems in due course, causing frequent machine breakdowns.

Because of these inherent limitations in the existing technologies, this work focuses on the use of a two-phase compressible cleaning mixture which helps overcome these problems to some extent.

1.3 Two-phase mixtures: The use of two-phase mixtures in cleaning applications has not been explored much. Tragardh and Bockelmann [9] presented mathematical models for calculation of pressure drop and mechanical cleaning effect for plant design of vacuum dairy milking pipes using an air-water mixture. Through their model, they found the cleaning effect to be influenced by the Reynolds number and the liquid fraction of the air-water mixture.

There are several interesting properties of a two-phase liquid-gas mixture that merit its investigation as a cleaning fluid. An air-water mixture is almost 4300 times more compressible (2×10^{-3} 1/KPa) than pure water alone (4.58×10^{-7} 1/KPa) as shown in figure 4. It can be seen that even a small volumetric percentage of air sharply increases the compressibility of the mixture over and above the value for the base water stream.
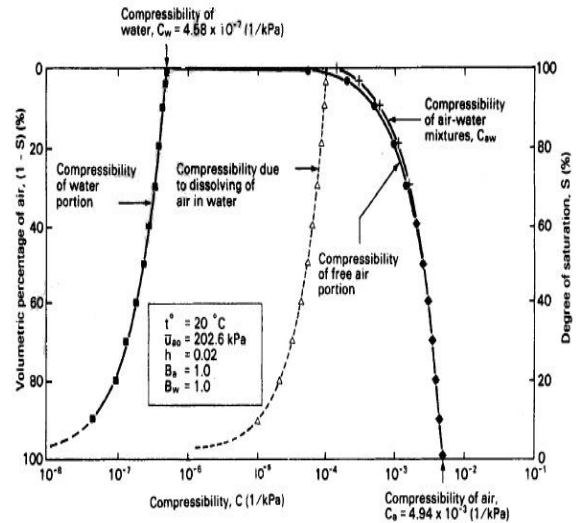

Fig. 4 Variation of compressibility of air-water mixture with respect to void fraction of air in the mixture

The pressure wave travels with the speed of sound in the medium. The speed of a pulse traveling in a 50% volumetric concentration of air bubbles in water at atmospheric pressure is about 19m/s, as shown in figure 5. Because of the reduced sonic velocity in an air-water mixture, it is possible for a weak shock wave possessing oscillatory structure to form in water with air bubbles, given specified relationships between the effective mixture viscosity, intensity of the disturbance, and bubble radius.
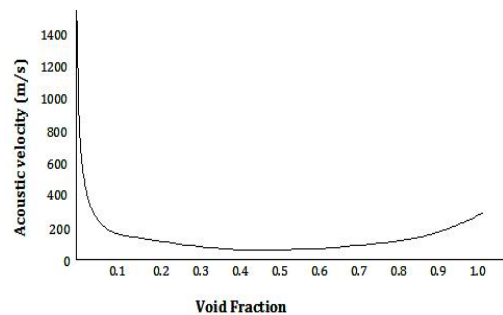

Fig. 5 Variation of acoustic velocity in an air-water mixture with respect to the void fraction of air

Literature review shows that propagation of pressure waves in a liquid with gas bubbles has been extensively studied both theoretically and experimentally [10-14]. The occurrence of solitary pressure waves called solitons has been discussed in bubbly liquid mixtures. It was found that heat exchange of the gas in the bubbles

with the ambient liquid in a wide range of parameters of the medium is the main mechanism of wave dissipation in bubbly media.

Dontsov and Nokaryakov [15] observed the pressure waves in a gas liquid medium with a stratified liquid-bubbly mixture structure and showed that the non uniformity of the bubble distribution over the tube cross section increases the attenuation rate of pressure waves. Voskoboinikov [16] et al. showed that it is possible to increase the percentage of shock-wave energy transmitted to the liquid by using a liquid mixed with gas bubbles as a transmission medium.

2. Experimental Setup: The experiments were performed at the production department lab, Daimler AG, Stuttgart. A schematic diagram of the experimental setup used is shown in figure 6. The diesel engine cylinder head OM 646 was used for the purpose. A cross section of the cylinder head passing through the water jacket was first made in Catia CAD software, to ensure two basic criteria are met: firstly, the volumetric flow rate of water passing through the water jacket does not fall below 75-80% of the original amount, so that actual cleaning conditions are maintained as much as possible. Secondly, the section should be made at an appropriate height in the water jacket so that the emerging landscape has characteristic bottlenecks representative of the actual cylinder head. A steel plate was used to cover the cross section of the head and bolted firmly into its top surface. Three Jumo dTRANS p32 pressure transducers were mounted on the steel plate at different distances from the inlet of the water-jacket to record the pressure variations at three bottleneck locations across the width of the head. The pressure transducers operate on the piezoresistive measuring principle. The fluid pressure was transduced into an electrical signal and captured with the help of LabView software, where it was calibrated to represent the information into corresponding pressure units (bars). The water circuit had an installed manometer to measure the incoming stream pressure, while the air circuit with a line pressure of 5 bars had an installed compressor with a 2:1 pressure ratio, to double the maximum usable pressure to 10 bars. A throttle valve allowed the use of intermediate pressure values by regulating the opening of the valve. Ball valves were installed in both the air and water circuits to be able to control the range of mixing compositions as described before. An exit valve at the water jacket outlet helped regulate the rate of flow of the mixture inside the head.

3. Range of operation: Figure 7 shows the range of a two-phase mixture composition measured in terms of void fraction of gas in the liquid. Under steady state, air is present in water as both dissolved and free air. The solubility of air in water occurs through the diffusion of air molecules into water.
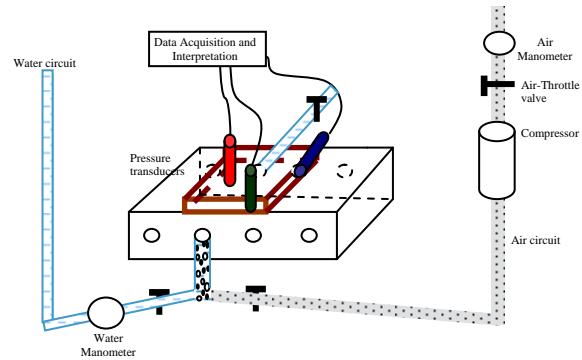

Fig. 6 A schematic diagram for the experimental setup used

The air-water mixing for a cleaning mixture is a transient turbulent process, and hence the component of dissolved air in the mixture is minimal. The free air is present in the form of spherical bubbles in the water stream as a spherical shape minimizes the surface energy of the bubbles. Measurement of finer parameters like bubble radius and the exact void fraction require more sophisticated experimental facilities.

For higher void fraction values (or conversely, a lower degree of saturation), water stream disintegrates into small lumps or packets that further disintegrate into fine droplets as they move through the air stream because of the aerodynamic drag. While the momentum imparted by these individual droplets on a surface has been shown to be significant [17], practical applications of this mixture composition is not useful for internal cleaning of complex geometries as the impacting water droplets fail to travel to the critical bottleneck areas located at relatively inner locations in the landscape.

For this work, a lower void fraction was deemed better because as can be seen in figure 4, the compressibility of the mixture increases rapidly even at small concentrations of free air. This allows us to use the properties of compressible mixtures to increase the pressure build up inside the head, while consuming low quantities of compressed air.
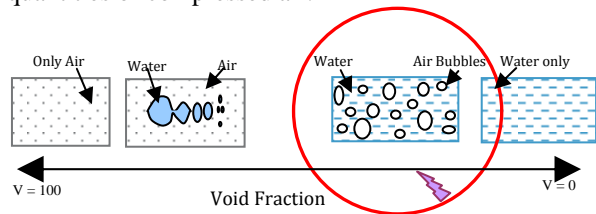

Fig. 7 Range of operation for a two-phase air-water mixture

4. Experimental Results: The water circuit had a constant tap water stream providing the flow of water. The inlet water pressure as measured with the line manometer was found to be 7 bars. The volumetric flow rate of water was measured to be 0.16 liters/sec. These conditions were unchangeable for the experiment because of the non-availability of a suitable water pump that could increase base pressures and an exit nozzle that could increase the water flow rate.

The inlet air pressure was varied over a range from 1 to 10 bars, but the results have been compiled here for 5 and 10 bar pressures for simplicity, with intermediate pressures giving intermediate results.

Figure 8 shows the base pressure measurements inside the cylinder head for any of the three sensors. It must be noted that the water jacket outlet was constricted in area by the use of a blocking plate with a relatively smaller orifice and a discharge pipe with an exit valve. Because of the reduction in area and hence a reduction in discharge flow rate, the fluid or the mixture streams could build similar pressure at all locations inside the head. Hence the plots shown in all figures hereafter are valid for any and every sensor location with minimal difference.

At the same time, the complex nature of streamlines in a complicated head geometry means that the sensor surface is never perpendicular to the direction of the flow and thus cannot bring the dynamic component of pressure to a stagnation value. Hence in many cases, the measured value is much lesser than the stagnation of flow brought about in a circular pipe. However, this is not really a problem as all the subsequent pressure measurements are compared to the base values measured in figure 8, and thus it is only the pressure ratios that this work keenly focuses on.
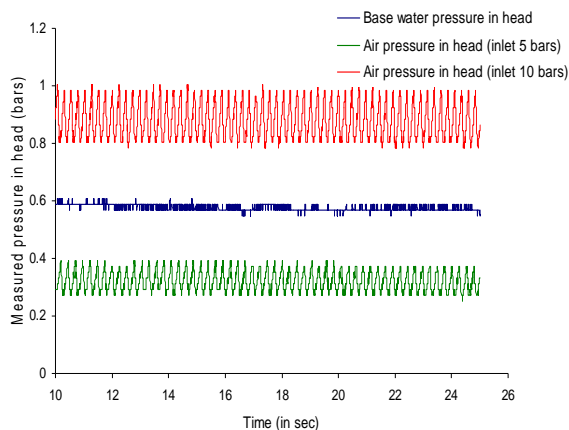

Fig. 8 Base pressure measurements in the cylinder head using the pressure transducers

The pressure experienced by a trapped contaminant chip in an actual case will be closer to the true stagnation values as the flow streamlines will be blocked by the surface area of the chip located in a bottleneck dimension, something that is not achievable through a sensor surface, because of constraints in fixing the sensors on the metal plate.

Figure 9 shows the pressure of the air-water mixture (with 30-40% void fraction) inside the head as measured by any of the sensors. The base air was taken at inlet pressures of 5 and 10 bars as explained before. It is clear from the figure that the pressure of the mixture is more than just the sum of individual air and water streams. This demonstrates the presence of compressibility effects in an air-water mixture.
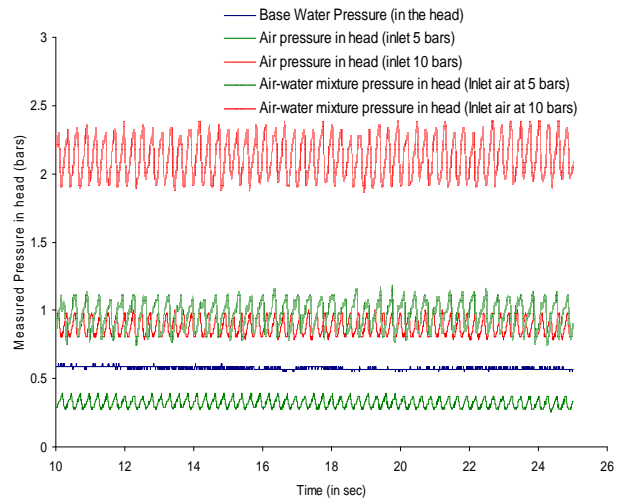

Fig. 9 Measurements of a homogeneous air-water mixture stream inside the cylinder head

Air alone tends to rapidly expand as soon as it enters inside the cylinder head and loses energy rapidly because of the several levels of obstruction caused by the complicated geometry of the head. Air carried by a water medium brings a cushion to the otherwise rapid energy loss of air.

In order to utilize the effects of compressibility of an air-water mixture to a more optimum extent, the following method called 'Air Pulsing' has been proposed and analyzed:

4.1 Air Pulsing: Figure 10 shows the mechanism of air pulsing as employed in this work.

The ball valve in the air circuit is opened and closed quickly to allow a small packet of air to get trapped in a continuously flowing water stream. This small packet

of air-water mixture is much more compressible (around 4300 times) than the surrounding water stream.
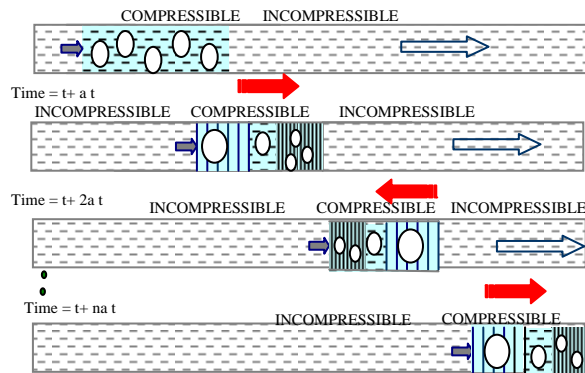

Fig. 10 Mechanism of 'Air Pulsing' and pressure wave propagation

Because of the continuously impacting upstream water on this packet, there is a pressure wave generated inside it. This pressure wave can develop into a shock wave under suitable conditions of flow rates and viscosity. This wave travels through the compressible packet through a series of compressions and rarefactions, which expand and diminish the air bubble sizes, according to the Boyle's Law of gases. These air bubbles under compression store pressure energy much like an automobile suspension spring stores energy when compressed. When this wave reaches the other end of the packet, it cannot travel into the surrounding incompressible water stream, and gets reflected from the boundary in the opposite direction. It thus continues to shuttle back and forth in the compressible packet dissipating its energy along the way. Since the mixing of the streams was done closer to the water jacket inlet, the extent of wave dissipation was reduced. When the packet finally gets discharged into the head, it undergoes sudden expansion, which causes a 'rapid release' (explosion) of the stored energy in a short duration (typically less than 1 second) burst. This causes the occurrence of pressure "spikes" with a frequency that matches the frequency of air valve opening and closing.

These spikes as detected by the sensors are shown in figures 11 and 12 for inlet air at 5 and 10 bars respectively. It can be seen that for the inlet air at 5 bars, the pressure peak is approximately 4 times the base water pressure, and for inlet air at 10 bars, the peak is almost 6.5 times higher.

4.2 Effect of valve opening and closing times: The air valve used to control the release of air in the water stream was a manually operated ball valve, with a switching time of the order of a fraction of a second.
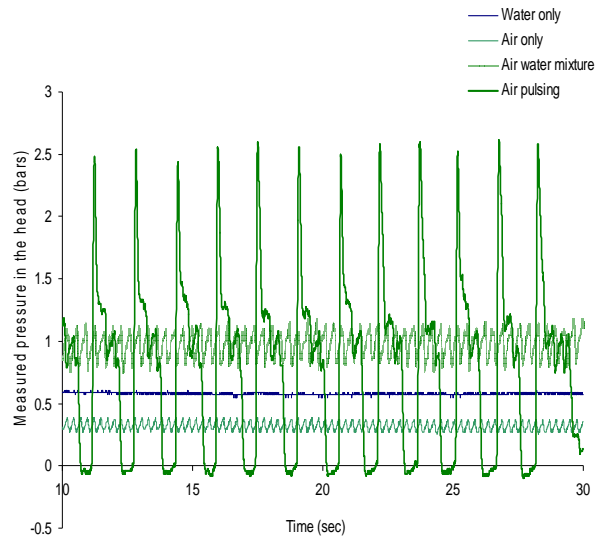

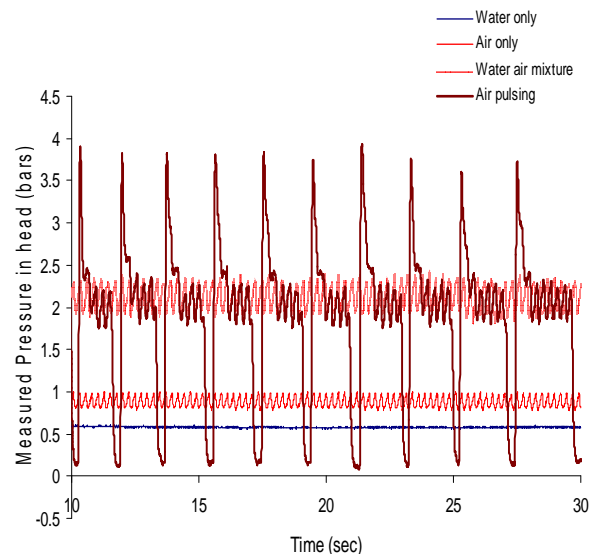Fig. 11 Air pulsing effects with inlet air at 5 bars

Fig. 12 Air Pulsing effects with inlet air at 10 bars

The amount of switching time directly influences the quantity of air inducted into the water stream. This in turn affects the extent to which the packet can be compressed. For an industrial application, the use of automated solenoid valves with a switching time of a few milli-seconds can help to trap a very thin air packet, which in turn compresses the trapped air-bubbles in the mixture much effectively using the impacting force of the surrounding water stream. The release of these highly compressed bubbles in that small compressible zone inside the head, generates a pressure spike that is taller and lasts for a shorter interval; effectively simulating a sharp impulse on a trapped contaminant. Figure 13 shows the effect of decreasing

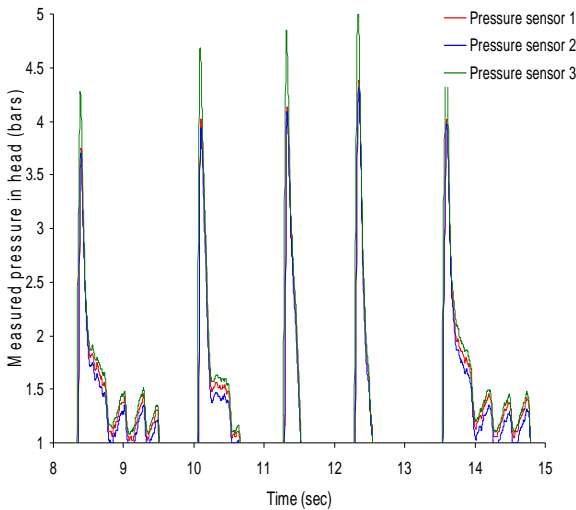the valve switching times on the magnitude of the pressure spikes.

Fig. 13 Effect of valve switching times on pressure surge

4.3 Effect of synchronous and asynchronous opening and closing of inlet and exit valves: The pressure development inside the head is favored by restricting the amount of discharge of the cleaning mixture out of the head. One way to achieve that is to narrow the water jacket outlet by the use of blocking plates that have a smaller orifice. Another complementary method is to use an exit valve that regulates the amount of mixture released from the head. The current experimental arrangement employs both these methods.

The timing of the opening and closing of the exit valve can be adjusted in accordance with the switching of the inlet air valve. Two particular cases are examined in figure 14. When the two valves are opened and closed in phase, there is an immediate outlet for the release of the pressure spikes dissipated in the head. This does not allow the pressure developed in the head to sustain for a little while. On the other hand, when the exit and the inlet air valves are opened and closed asynchronously, then the pressure released inside the head is allowed to build up momentarily, giving a higher pressure spike as shown in the figure.

It must be noted though that the closing time of the exit valve is critical because while the contaminants are being removed, they can be transported to a different area inside the head if they do not particularly find any outlet. Thus there is a tradeoff to consider, and an optimum value for the switching time of an exit valve should be further investigated.
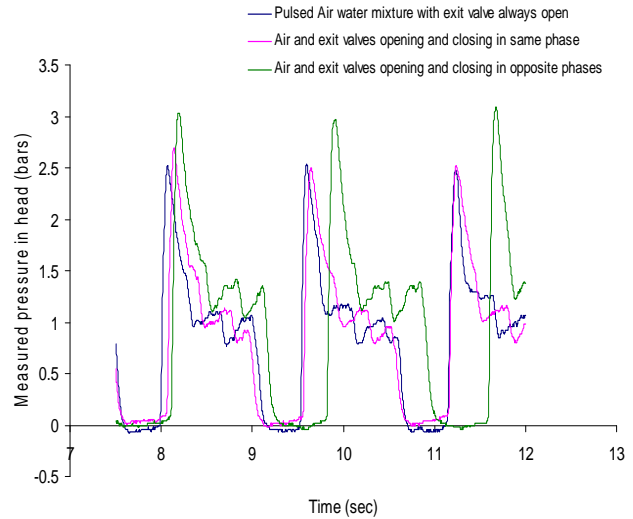

Fig. 14 Effect of in-phase and out-of-phase opening and closing of inlet air and exit valves

5. Sensitive fluid flow parameters for a two-phase mixture: The flow rate of the water stream is a sensitive parameter of interest. A higher flow rate provides a higher impacting force on the trapped compressible mixture packet which can lead to a stronger pressure pulse traveling through it.

For a given flow rate, the optimum values of inlet air and water pressure are also important to explore in order to exploit the compressibility effect to the maximum extent possible.

Finally from a mixture perspective, the percentage of air by volume (void fraction) can be controlled from a performance and cost perspective as the use of compressed air in large quantities can not just be detrimental towards the efficiency of the method but it can be expensive to obtain in industry, on a production scale.

An attempt to fix some of these parameters can be done by plotting a family of non-dimensionalized pressure ratios as shown in figure 15. The figure shows two such ratios for a given pressure and flow rate of water. The shape of these curves is characteristic across the entire family. The curves have been extrapolated after passing a best-fit polynomial through the data points corresponding to inlet air pressures of 4, 7 and 10 bars. It should be noted that the extrapolation is most useful when the data points cover a significant domain of the curve shape. Thus for different flow rates and pressures of water, the range of experiments might need to be varied (in terms of usage of inlet air pressure) to generate a reasonably accurate family.
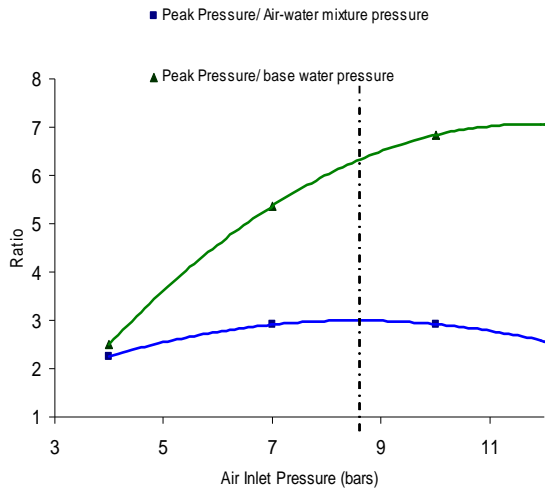
Fig. 15 Pressure ratios for determining sensitive mixture parameters

From the figure 15, it can be seen that the rate of peak pressure (corresponding to the spikes) increase relative to the inlet air pressure decreases for a given base water pressure. This is because as the air pressure in the mixture becomes very high, compressibility of the mixture reduces. This can be seen with the help of figure 16 which shows the mixture compressibility plots for a range of inlet air pressures and the suitable range of mixture void fraction for ideal operation as highlighted on the figure.
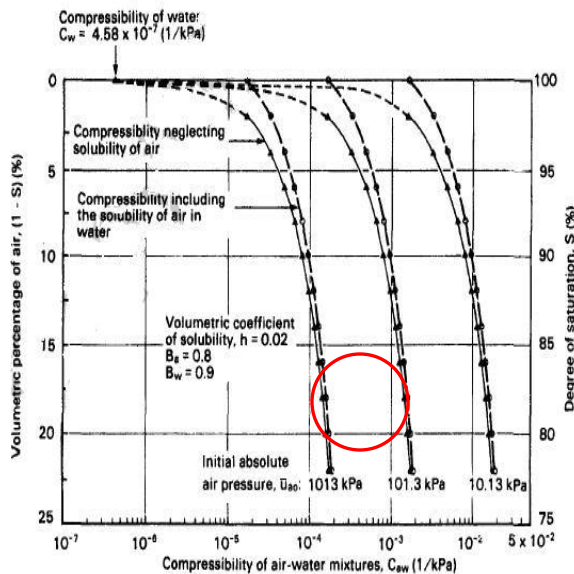

Fig. 16 Effect of inlet air pressure on the compressibility of an air-water mixture

However, when the ratio of the peak pressure to mixture pressure is plotted, it is found that the ratio increases till a particular value of inlet air pressure, beyond which it starts decreasing. The point at which this ratio is maximum can be used to set the optimum inlet air pressure. Comparing this point across a family of curves with different water pressures and flow rates and finding the one with the highest ratio, will set the required stream pressure and flow rate values. The void fraction of the mixture can be set using figure 4, according to which even with a 20-30% volumetric ratio of air in water, the mixture compressibility is quite high.

6. Comparison of Two-phase mixture cleaning and Impulse cleaning technology:

From an energy perspective, a two-phase mixture requires a lesser volumetric flow rate of water than the impulse cleaning method. Similarly the base pressure of the water stream in a mixture cleaning is lesser. Because of this, a two-phase mixture requires a much smaller pumping power and the associated costs involved.

From a performance perspective, there is at least an equal potential to generate comparable peaks or impulses. Some of the ways to magnify the pressure spikes are: using automated solenoid valves to limit the amount of air entering into the water stream, raising the volumetric flow rate of water to increase the magnitude of impacting disturbance on the compressible packet; and exploring the parameters for high amplitude pressure wave generation.

Another reason why on a performance aspect a two-phase mixture scores over the impulse cleaning is that the mixture is able to create high amounts of turbulence and vorticity in the cylinder head. This turbulence can prove useful is re-orientating trapped chips thereby aiding in their removal.

Finally from a repair and maintenance perspective, a two-phase mixture greatly mitigates the effect of water hammer faced by impulse cleaning. This is predominantly due to the fact that with air pulsing in a water stream, the continuity of the base water stream is always maintained. Secondly, the presence of air provides an elastic cushion to the secondary hammer impacts generated from pipe bends and area changes.

7. Conclusions: This work provides an insight into a possible new technology, i.e. the use of two-phase mixtures, for the design of a next generation of cleaning machines in the automotive industry for complex internal cleaning applications. A method of air-pulsing

has been proposed to utilize the property of compressibility of these mixtures to generate comparable pressure spikes as the impulse cleaning method. Advantages of using a mixture cleaning over the existing technology have been expressed in terms of meeting performance goals, reducing the energy requirements and costs of frequent maintenance and breakdown because of the water hammer effect.

9. References:

[1] M. Ávila, J. Gardner, C. Reich-Weiser, A. Vijayaraghavan, S. Tripathi, D. Dornfeld, "Burr Minimization Strategies and Cleanability in the Aerospace and Automotive Industry", SAE Transactions, Paper 2005-01-3327.

[2] C. Reich-Weiser, D. Dornfeld, "Experimental Investigation of the Influence of Machining Parameters on Chip Geometry for Enhanced Cleanability", Laboratory for Manufacturing and Sustainability, Consortium on Deburring and Edge Finishing, 2006.

[3] M. Ávila, D. Dornfeld, K. Berger, "Analysis of residual chip geometries during Impulse machine cleaning tests", Summer Research, DaimlerChrysler, Stuttgart, Germany, 2006.

[4] D. Arbelaez, M. Avila, A. Krishnamurthy, W. Li, Y. Yasui, D. Dornfeld, S. McMains "Cleanability of Mechanical Components", Proceedings of NSF Engineering Research and Innovation Conference, Knoxville, Tennessee, 2008.

[5] S. Garg, D. Dornfeld, K. Berger, "Formulation of the chip cleanability mechanics from fluid transport", Proceedings of the International Conference on Burrs – Analysis, Control and Removal, 2009.

[6] D.G. Smith, R. Kinslow, "Pressure Due to High-velocity Impact of a Water Jet", Experimental Mechanics, vol. 16, pp. 21-25, 2006.

[7] C. Wulff, "Impulse Jet Cleaning at Daimler", Masters Thesis, Daimler AG, Stuttgart, Germany, 2006.

[8] J. Evans, "Waterhammer – Its all about conserving Energy", www.pumped101.com

[9] C. Tragardh, I.V. Bockelmann, "Mechanical Cleaning Effect and Pressure Drop of Air-water flow in horizontal glass tubes (Vacuum Dairy Pipelines)", Journal of Food Processing Engineering, vol. 3(2), pp. 77-90, 1980.

[10] G.K. Batchelor, "Compression waves in a suspension of gas bubbles in a liquid", Mechanics (collected scientific papers) [Russian translation], vol. 109(3), pp. 67-84, 1968.

[11] L.V. Wijngaarden, "On the equation of motion for mixtures of liquid and gas bubbles," Journal of Fluid Mechanics, vol. 33, pp. 465-474, 1968.

[12] V.E. Nakoryakov, B.G. Pokusaev, I. R. Shraiber, Wave Dynamics of Gas and Vapor-Liquid Media, Energoatomizdat, Moscow, 1990.

[13] R.I. Nigmatulin, Dynamics of Multiphase Media, Part 1, Hemisphere, New York, 1991.

[14] M. Watanabe, A. Prosperetti, "Shock waves in dilute bubbly liquids," Journal of Fluid Mechanics, vol. 274, pp. 349-381, 1994

[15] V.E. Dontsov, V.E. Nakoryakov, "Pressure waves in a gas-liquid medium with a stratified liquid-bubbly mixture structure", Journal of Applied Mechanics and Technical Physics, vol. 44(4), pp. 538-542, 2003.

[16] I.M. Voskoboinikov, B.E. Gelfand, S.A. Gubin, S.M. Kogarko, O.E. Popov, "Utilization of liquid-gas bubble mixtures for the transfer of shock wave disturbances", Translated from Inzhenerno-Fizicheskii Zhurnal, vol. 31(4), pp. 674-671, 1976.

[17] M.M. Vijay, "Ultrasonically generated cavitating or interrupted jet" U. S. Patent No. 5,154,347