

The Development of a Superheated Liquid Flash, Boiling (S.L.F.B) Engine for Waste Heat Recovery from Reciprocating Internal Combustion Engines

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ABSTRACT

High temperature liquids held in a subcooled state are capable of storing large amounts of energy and then explosively releasing this energy when depressurized in a phase change process known as "Flashing". The rapid volume expansion that results from this flashing has been harnessed to drive an expansion engine working on a cycle called "The Superheated Liquid Flash, Boiling" (S.L.F.B) cycle. The first stage showed that multiphase convective boiling of the unflashed water off the heated walls of the expansion unit supplemented the Flash work output. Furthermore, Flashing was seen to improve the effectiveness of convective boiling off the walls. The results were shown to be repeatable in a modified piston engine. Convective boiling was again shown to be able to supplement the power output under specific conditions. Engine power was seen to be directly related to the peak In-Cylinder pressure, which in turn was directly related to the mass and temperature of the injected subcooled water. The efficiency of the engine was directly related to the mass and level of subcooling of injected working fluid up to a boiling plate temperature of 215°C but inverted in relationship at boiling plate temperatures between 289°C and 297°C. This is hypothesised to be due to the effects of residual liquid mass caused by the Leidenfrost effect. The effective removal of the residual liquid mass during the exhaust stroke is expected to improve the overall efficiency of the engine.

CITATION: Hewavitarane, D., Yoshiyama, S., Wadahama, H., and Li, X., "The Development of a Superheated Liquid Flash, Boiling (S.L.F.B) Engine for Waste Heat Recovery from Reciprocating Internal Combustion Engines," *SAE Int. J. Engines* 7(4):2014, doi:10.4271/2014-01-2592.

INTRODUCTION

Waste Heat Recovery

The world of today is faced with many issues. The insatiable appetite for energy resources is a particularly important one as most of the world's conflicts can be traced back to this. As our modern society has developed around fossil fuels, the efficient and prudent use of this limited resource has become one of the most important issues facing modern environmental engineering. The main consumer of fossil fuels is the transportation system. With the ever-growing prosperity of the emerging economies, the demand for new automotive vehicles in these nations is putting even more stress on petroleum reserves. In addition to this stress, the carbon dioxide emissions from these new engines and the engines currently in use are another contributor to the Green

House Effect. While zero emission vehicles are arguably the ideal means of transportation, the implementation of the infrastructure required to make them viable is still many years off and in their current forms, both cost and resource inhibitive. The fact of the matter remains that while there are fossil fuels, society will continue to use them. It thus becomes the goal of the engineer to make the current fossil fuel based technologies such as Internal Combustion engines, more efficient. This will allow future generations to transition into a zero emission transportation system in a more economically sustainable manner without further contributing to the multitude of problems current society faces. Furthermore, the internal combustion engine remains a candidate for the future as bio fuels would allow these engines to continue operating even when no more fossil fuels remain.

While the reciprocating IC engine has undergone vast improvements in its efficiency, the most efficient road going engines today remain just under 45% and the average engine remains at approximately 35%. Even if the Otto and Diesel cycle engines were to achieve the pinnacle of their efficiencies, it is now generally accepted that mass production automobile engines will never exceed the 50% mark due to several limitations owing to practicality. In most automotive situations, it is common for 30% of combustion heat to be lost in exhaust gases and a further 35% through heat transfer to the cylinder walls and through coolant. The harnessing of this waste heat is the key to improving the overall efficiency of an internal combustion engine and Automotive Waste Heat Recovery (AWHR) research has gained momentum in recent years. Unlike conventional waste heat recovery systems, one of the major hurdles faced by AWHR systems is size. The ideal AWHR system needs to be compact and efficient, and the ease of being integrated to the powertrain would be highly advantageous as well.

Current Systems

While many forms of waste heat recovery exist, the most keenly researched include the Rankine cycle, Organic Rankine Cycle (and combinations of these), Thermo-electric, Turbocharging and Sterling cycles [1]. A relatively new cycle known as the Trilateral Cycle (TLC) [3] is also showing promise. The commonality shared by a lot of these systems is the requirement of an intermediate storage system for the energy they produce and in most cases this is an electrical battery. As necessity dictates, an electrical power generating system is part of the package as well. The usage of batteries, while an obvious choice, brings with it the drawbacks of current electrical battery technology which include low power storage to weight ratio, relatively short life spans and high cost. While some waste heat recovery systems allow direct power delivery to the power train, it can be hypothesized that they would suffer from poor transient response due to the nature of their expansion units and not allow for "on-demand" power delivery.

The Proposed System

A WHR system that allows on-demand direct power delivery to the power train with good transient response is the ultimate goal. Such a system has been envisioned by the authors. The key feature of the system is its use of a working medium that is kept in its liquid phase for storing energy and then converted to its vapour phase, releasing its stored energy in the power generation unit. The cycle on which this system works has similarities to the TLC with its key benefit [2],[3],[4],[5]. Furthermore, the working medium in its liquid phase is comparable to a liquid fuel which has inherent benefits such as its relatively small volume and ease of handling [11]. Superior transient response and good efficiency is also achievable by the use of a compact positive displacement reciprocating power unit. Figure 1 shows the proposed WHR system.

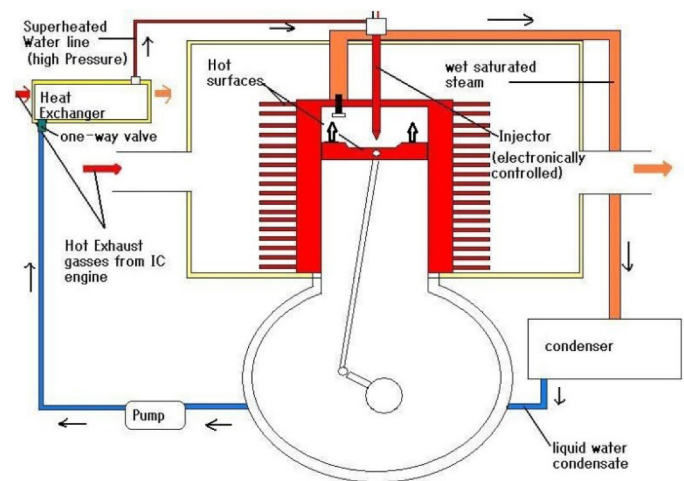


Figure 1. The proposed WHR system based on a SLFB Cycle power unit.

Flashing

A high temperature liquid held in its liquid phase by a high vapour pressure is termed a subcooled liquid. When this subcooled liquid is released into a lower vapour pressure environment, the liquid phase can hold less heat and must "dump" some of this energy. This "dumping" occurs by converting a certain portion of the liquid into the gas phase and the unflashed portion of the original liquid falls to its new and lower saturation temperature. The phase change described above is an almost instantaneous process and is known as "Flashing". Flash steam enthalpy is the difference between the enthalpy of the high pressure subcooled water and the enthalpy of the liquid phase of water at the lower vapour pressure of the environment it enters. The work potential of this steam comes from this heat which it possesses. The vapour content of the wet steam generated by flashing can be described by equation (1).

$$x = \frac{h_{isl} - h_{fvp}}{L_{fvp}} \quad (1)$$

x is the vapour quality of the steam generated. It is this vapour fraction that is capable of doing work through volume expansion. Furthermore, the specific heat possessed by this vapour can be described by equation (2)

$$h_{fs} = h_{isl} - h_{fvp} \quad (2)$$

The Superheated Liquid Flash, Boiling Cycle and its Similarities to the Trilateral Cycle

The SLFB cycle proposed in this paper has similarities to The Trilateral Cycle [2],[3],[4],[5]. The ideal TLC may be summarized by Figure 2.

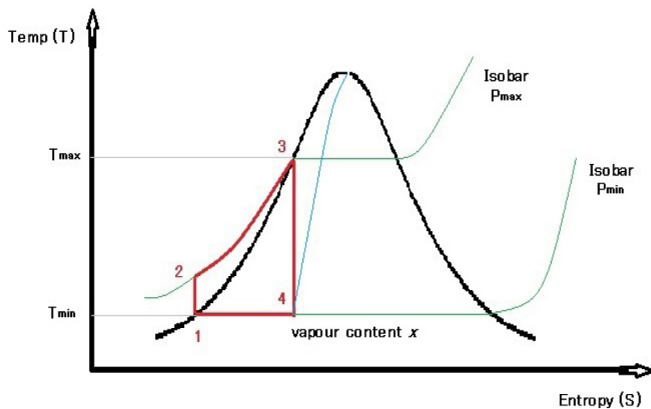


Figure 2. The TS Diagram of the TLC

1-2 is the isentropic compression of the liquid phase to a maximum pressure P_{max} by an isentropic pump. The pump compresses the liquid to a pressure high enough to maintain it in a subcooled state at T_{max} . 2-3 is the isobaric heating of the liquid phase up to the temperature T_{max} . At state 3 the liquid is in a superheated state. 3-4 is the isentropic expansion of the vapour generated from “flashing”. In this process, wet saturated steam is generated as the temperature of the working fluid drops to the temperature T_{min} and pressure P_{min} with vapour content x . 4-1 is the condensation of the wet vapour back to state 1.

The ideal SLFB cycle can be summarized by Figure 3.

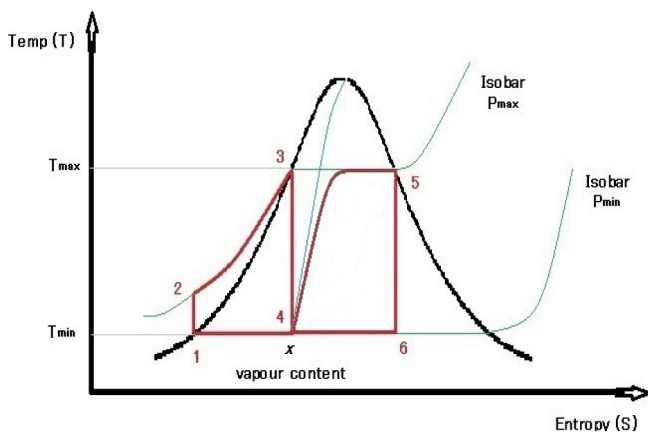


Figure 3. The TS Diagram of the ideal SLFB Cycle

The SLFB cycle is identical to the TLC in process stages 1-2, 2-3 and 3-4. Stage 4-5 is the multiphase convective boiling of the wet portion of steam generated in process stage 3-4, from the heated walls of a specially designed component within the expansion unit. The vapour generated is capable of reaching a maximum pressure of P_{max} determined by the internal wall temperature T_{max} . 5-6 is the isentropic expansion of the vapour generated. 6-1 is the complete condensation of the vapour back to state 1. It can be said that the SLFB cycle is an augmented version of the TLC. The “B” in the cycle’s acronym

“SLFB” stands for this convective boiling process. The multiphase convective boiling supplements the work output of the cycle, and simultaneously helps reduce the wetness of the vapour generated in the process stage 3-4. This is important as it reduces the mass of liquid phase within the expansion unit which can be detrimental to its mechanicals.

Unique Aspects of the SLFB System

The unique aspects of the SLFB system are as follows:

1. The working fluid (superheated water) is delivered directly into the expansion unit using a fast response electro-mechanical injector which allows fine control of the timing and mass of working fluid injected.
2. Work is generated in the power unit from two processes; (a) The flashing of the superheated working medium and (b) The multiphase convective boiling of the unflashed liquid portion by heat transfer from heated surfaces within the power unit.

The principle of operation of the SLFB engine is illustrated in Figure 4.

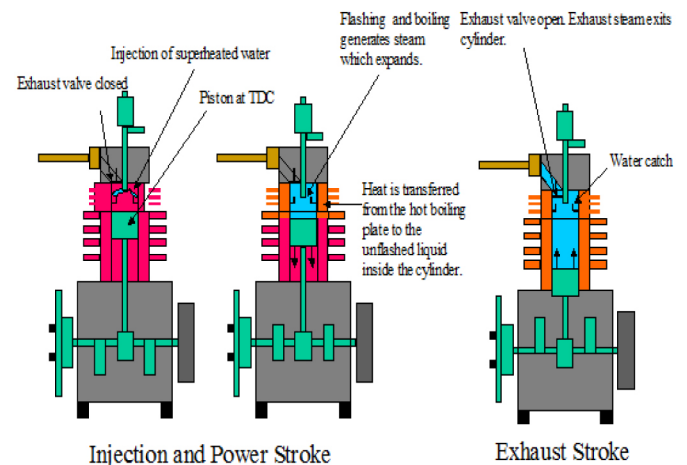


Figure 4. The 2-Cycle SLFB piston engine.

OVERALL AIM

To investigate the nature of Flashing and Convective Boiling and its ability to generate power in a positive displacement reciprocating expansion power unit.

THE EXPERIMENT OUTLINE

The experiment was carried out in 3 main stages.

Stage 1: *The construction of an injector:* The construction/modification of an electrically controlled injector capable of operating under the conditions of this experiment was the first and one of the most important goals of this experiment. This enabled the second and third stages to be carried out.

Stage 2: The high temperature subcooled water injection experiments: This stage was carried out to determine the potential of the flash, boil processes to generate work.

Stage 3: The powering of an engine with the SLFB cycle: This stage investigated the SLFB cycle's ability to produce power in a piston engine.

Stage 1: The Construction of an Injector

As the design and construction of an injector was beyond the scope of this research, a commercially available common rail diesel injector was chosen. A Bosch First generation solenoid actuated common rail diesel injector (CRI 1) used in the Toyota 1ND-TV engine was modified for use in the SLFB cycle engine. A common rail diesel injector was chosen as its all metallic design coupled with its high injection pressures made it the most suitable for injecting high temperature subcooled water. As this injector uses a high speed solenoid which is sensitive to heat and requires cooling when in normal operation, a cooling adapter was designed to protect the heat sensitive solenoid. The adapter included a liquid coolant circulation system to cool the solenoid while in operation. Other modifications included those to the internals which allowed injection at pressures starting from 3MPa and the enlargement of the nozzle tip orifices' diameter from the standard 125 μ m to 400 μ m to increase the mass flow rate. The modified injector is pictured in [Figure 5](#).

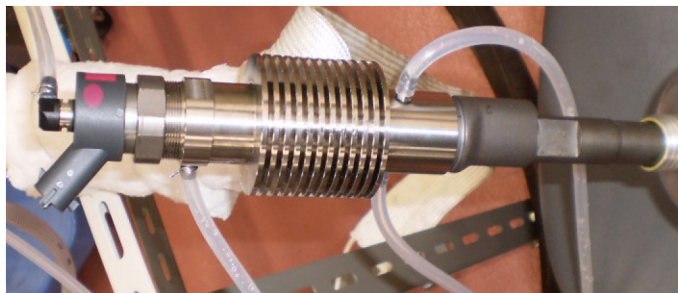


Figure 5. The Modified Bosch Common Rail Diesel Injector used for injecting subcooled water.

The modifications allowed stable operation of the injector with the desired mass flow rate.

Stage 2: The High Temperature Subcooled Water Injection Experiments

[Figure 6](#) illustrates the experimental setup used for investigating the SLFB process.

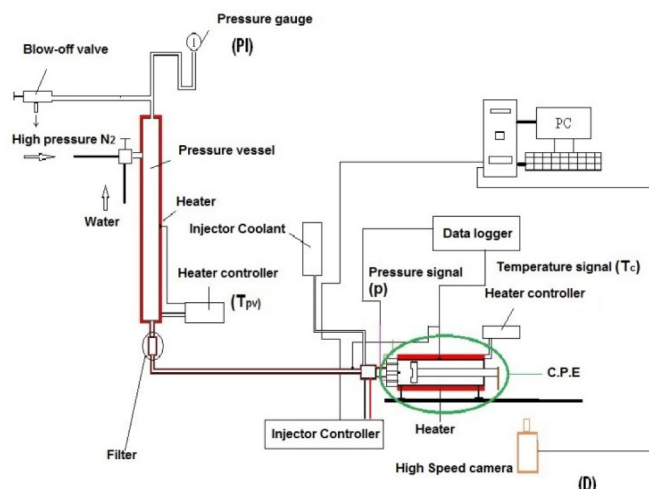


Figure 6. The Experimental Set-up for investigating the SLFB process.

Pure distilled water was heated in a pressure vessel up to a temperature of 240°C and maintained in a subcooled state at a vapour pressure of 5MPa by compressed Nitrogen. A pressure of 5MPa was used in order to achieve adequate injection mass flow rate and to ensure that the level of subcooling was high enough that flashing only occurred at or very close to the exit of the injector nozzle tip orifices and not within the injector or delivery pipes. Each injection experiment consisted of 50 consecutive injection events. The injected mass was varied by varying the injection duration. The first set of experiments used a 15ms ON duration with a 1ms OFF duration between each injection. Experiments were carried out using a Constant Pressure Expander (CPE) with wall temperatures (T_c) of 80°C, 120°C, 130°C, and 140°C. The start of the injection simultaneously triggered the gathering of pressure data by a high speed data logger and video by a high speed video camera. The data gathered from the pressure sensor output and the video from the high-speed camera were used to plot a Pressure vs Volume graph for each injection experiment. This graph was then used to calculate the indicated work (W_i) done by the expanding steam for the duration of the injections. After the first set of experiments, it became clear that the subcooled water was losing a significant amount of heat to the CPE head prior to injection and accurate knowledge of the injected water temperature could not be established. To achieve near adiabatic conditions, the injector and subcooled water had to be kept at a temperature that was equal to the T_c , as this temperature is also the temperature of the CPE head on to which the injector is connected. This mitigated any heat loss from the subcooled liquid prior to injection. The temperature at which the CPE could safely be maintained for extended periods of time was 130°C and so the temperature of the superheated water was also maintained at 130°C and injection experiments repeated for 50 $\times$ 10ms ON and 1ms OFF followed by 50 $\times$ 5ms ON and 1ms OFF. Injection experiments

were also carried out with non-flashing injection of $50 \times 5\text{ms}$ ON and 1ms OFF for water temperatures (T_{pv}) of 70°C and 90°C with a T_c temperature of 130°C .

Results

The Indicated work was calculated according to [equation \(3\)](#). v_i is the volume of the CPE at injection initiation and v_f at the end of injection. P is the constant pressure at which expansion took place within the CPE.

$$W_i = \int_{v_i}^{v_f} P dv \quad (3)$$

The enthalpy of Flash steam was calculated according to [equation \(4\)](#). This enthalpy is a function of the pressure within the cylinder as is the specific enthalpy of the liquid at the final vapour pressure, and is thus denoted as $H_{fs}(P_{cyl})$ and $h_{fvp}(P_{cyl})$ respectively.

$$H_{fs}(P_{cyl}) = (h_{isl} - h_{fvp}(P_{cyl})) \cdot m_i \quad (4)$$

In the CPE experiments, the expansion occurs at a constant pressure, thus $p_{cyl} = \text{constant}$ and this constant pressure was used to determine the h_{fvp} .

The efficiency with which the enthalpy of Flash steam was converted to work was calculated according to [equation \(5\)](#). E_v is termed the efficiency value.

$$E_v = \left[\frac{W_i}{H_{fs}} \right] \cdot 100 \quad (5)$$

An E_v value of 100 relates to the engine's work output being equal to the enthalpy of flash steam generated by the injected mass of subcooled liquid. Values larger than 100 indicated an input of energy in addition to that of the flash steam energy. [Figure 7](#) illustrates the experiment procedure of the CPE injection experiments. [Figure 8](#) shows the efficiency values at various CPE wall temperatures.

It can be seen that a wall temperature of 80°C all but removes the workout put of flashing. This is due to condensation of the flash steam. Furthermore it is clear that as the wall temperature increases, the efficiency also increases. The relatively low efficiencies can be attributed to heat lost from the subcooled water prior to it being injected. [Figure 9](#) shows the efficiency values when the injections were carried out at near adiabatic conditions. The subcooled water is at a temperature of 130°C (T_{pv}) as is the CPE temperature (T_c).

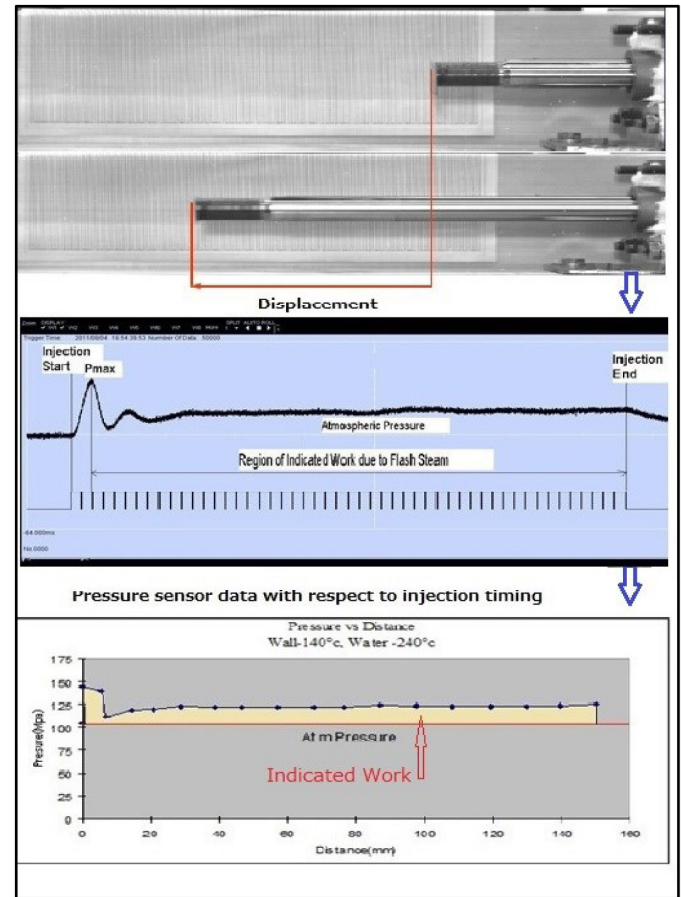


Figure 7. The Experimental procedure of Stage 2.

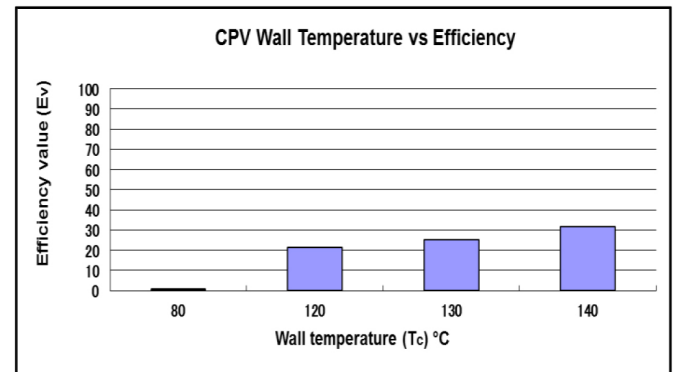


Figure 8. The efficiency of conversion of flash steam enthalpy to expansion work within the CPE for injections of subcooled water at a temperature of 240°C (T_{pv})

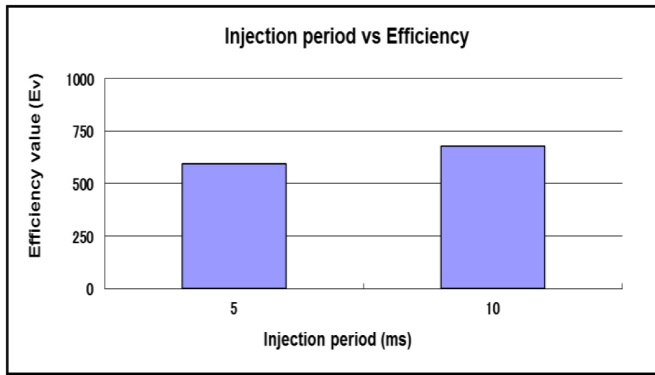


Figure 9. The results of the experiment carried out under near adiabatic conditions where no heat is gained or lost by the injected fluid prior to it being injected

By the definition of efficiency value in equation (5), it can be determined that an additional source of energy input was present as the indicated work output was larger than that possible from flash steam alone. This additional work is the multiphase convective boiling of unflashed water off the CPE walls (Q_{cb}). This convective boiling input may be described by equations (6) and (7).

$$Q_{cb} = C(T_s - T_l) \cdot A_{cl} \quad (6)$$

$$Q_{cb} = B_s \cdot L_l \quad (7)$$

T_s and T_l are the temperatures of the surface and liquid striking the surface respectively. A_{cl} , L_l and C refer to the area covered by the liquid striking the surface, the latent heat of vaporisation of the liquid striking the surface and the coefficient of heat transfer respectively.

The speed of boiling can be described by equation (8).

$$B_s = \frac{C(T_s - T_l) \cdot A_{cl}}{L_l} \quad (8)$$

The boiling speed B_s is the determining factor in the ability of convective boiling to contribute to power output of an SLFB engine as piston speeds increase.

Figure 10 shows the indicated work for non-flashing injections in comparison to a flashing injection. The CPE wall temperature is at 130°C and the injected water temperatures are at 70°C, 90°C and 130°C.

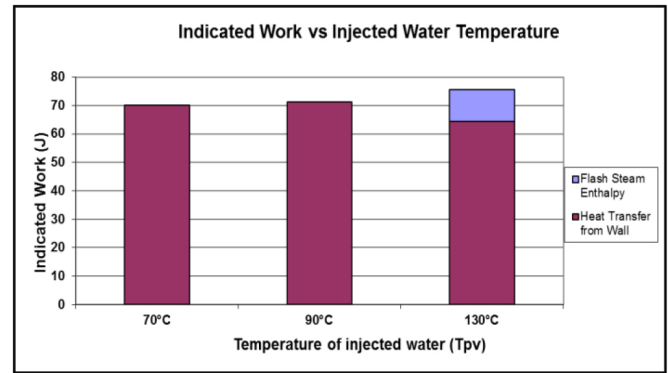


Figure 10. The results of non-flashing injections when compared to flashing injections into the CPE with a wall temperature of 130°C.

While there is no significant change in the convective boiling work output for temperatures of 70°C and 90°C, the contribution of convective boiling off the wall reduces when flashing occurs. As noted earlier, the contribution of convective boiling is dependent on the mass of liquid striking the hot wall, the surface area of the wall it covers and the boiling speed. Flashing which occurs at 130°C, causes a choked flow which reduces the mass flow rate of the injector. So less liquid strikes the hot wall. Furthermore, the liquid phase of the wet steam exiting the injector is at a relatively higher temperature than the non-flashing injections. As boiling speed is dependent on the temperature difference between the bulk of the liquid and the hot surface, i.e. the larger the difference the faster the boiling speed, the smaller temperature difference between the wall and the liquid phase of the flashed water further reduces the contribution of convective boiling. When taking into account the reduction in mass flow rate of the injector due to flashing flow (choked flow), the reduction in the mass of liquid water striking the walls and other effects such as reduced boiling speed, a total reduction of more than 11% in convective boiling work is expected. However the results show a reduction of only 8.89%. Research in the field of heat transfer has shown that spray cooling can increase CHF values and more efficiently transfer heat off hot surfaces when compared to jet flows of the same mass flux [13],[14],[15],[16]. Investigations by the authors into the injection patterns of non-flashing and flashing injections from the injector indicates a significant widening of the spray cone angle due to flashing. This would in theory translate to a larger area of the heated internal surface of the cylinder being impacted by the unflashed liquid portion. Furthermore, research on flash boiling and atomization has shown enhanced atomization through flashing [6],[7],[8]. It can thus be hypothesized that the smaller than expected decrease in convective boiling work for flashing injections was due in part to the enhancement of heat transfer from the walls of the CPV resulting from flash induced atomization of the liquid striking the walls. Figure 11a shows a non-flashing injection at a liquid temperature of 70°C and Figure 11b shows a flashing injection at a liquid temperature of 130°C.