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ABSTRACT

Some Electronic Throttle Control (ETC) Air Control Valves (ACV) on automotive internal combustion engines are susceptible to icing of the throttle valve. Ice formation can result in an increase in torque required to open or close the valve. Laboratory studies were conducted to improve the understanding of throttle valve icing on electronic throttle control valves with both aluminum and composite (plastic) bodies over various bore sizes (4 cylinder to 8 cylinder engines). Study results indicated that ice compression at the bore and valve gap, not ice adhesion, is the major contributor to the ETC-ACV icing phenomenon. In addition, testing of parts with various bore sizes, orientations and surface cleanliness resulted in further understanding of the icing issue.

INTRODUCTION

Throttle icing on multi-point fuel injected electronic throttle controlled (ETC) automotive gasoline internal combustion engines (ICE) can cause engine stalls and idle instability resulting in vehicle owner dissatisfaction or, in extreme situations, pose safety risks. The National Highway Traffic Safety Administration (NHTSA) has issued service bulletins and recalls due to throttle icing [1]. Field failures have also been reported in cold weather climates [2, 3].

Throttle icing can be divided into two categories. The first category is the adhesion of ice to the stationary throttle bore wall and valve area after the vehicle has been shut down after an extended drive. This icing is typically called “soak icing”. This throttle icing condition can cause the electronically actuated throttle to close improperly thereby not controlling the air into the engine. This lack of control in airflow can cause engine stalls and idle instability issues. The ice formation in the throttle can also occur during the operation of the vehicle with the throttle at various positions due to a high incoming moisture concentration. This type of icing is typically called “run icing”. “Run icing” can cause the throttle plate to stick in the open position, also resulting in the inability to control air flow. This paper will focus on ‘soak icing’ since experience of the authors has shown this to be more prevalent in the field.

The two major sources of water vapor are the Positive Crankcase Ventilation (PCV) system and Exhaust Gas Recirculation (EGR) system. Water vapor contained in the ambient air inducted into the engine represents a small part of the moisture that can lead to ice formation on the throttle. This is due partly to the fact that at low temperatures relative humidity is usually also low.

Icing tests in general are conducted at a vehicle level in cold ambient conditions. These icing tests usually consist of doping of the engine oil with water and/or fuel to duplicate short drive cold weather conditions. Under these conditions, engine oil can contain up to 4% of water and 11% fuel [4]. Typically, vehicle icing tests can only be performed on a small sample size of vehicles with limited variation of throttle design options. These tests can be expensive and require significant test time to assess the throttle for icing build up and the ability of the throttle to dislodge ice that may have formed.

The focus of this study was to develop a repeatable throttle component icing test that duplicated vehicle icing tests to accomplish the following objectives:

- Identify the mechanism of throttle valve sticking due to icing.
- Identify the effects of plastic vs. metal materials and bore size with respect to ice breaking torque at the throttle.
- Assess part orientation and surface contamination with respect to ice breaking torque at the throttle.
- Assess the industry standard excess torque specification of 1.6 – 3.5 N-m as tested at -30 to -40°C.

Through the understanding of the above objectives, throttle design improvements can subsequently be explored to reduce the field issues caused by throttle icing.

EXPERIMENTAL

Industry standard icing tests for automotive throttle valves (for example, SAE or ASTM) have not been published. The vehicle and laboratory icing tests discussed in this paper were developed internally based on experience and knowledge of environmental factors that contribute to throttle icing conditions.

Vehicle icing tests were performed prior to the development of the laboratory component icing tests. To cause vehicle ETC-ACV icing, water was added to the crankcase engine oil followed by a controlled drive cycle and cold soak at -15 °C. After the cold soak, the engine was allowed to idle and the throttle valve position was monitored. Recorded data showed that the ETC-ACV was not reaching the commanded throttle position. A visual examination of the valve showed ice had formed on the throttle valve and bore interface. The vehicle test parameters and the appearance / location of the ice were used as benchmarks for the laboratory component icing test development described in the following sections.

ETC-ACV COMPONENT PART DESCRIPTIONS – A variety of parts from various manufacturers were included in the study. A summary table is shown in Table 1. The “torque at ETC throttle shaft” is defined as the torque at the throttle shaft from the motor gear train at room temperature tested at 13.5V with the current limited to 6 amps.

TABLE 1. ETC-ACV Part Descriptions

Part Design Type	No. of Samples	Bore Diameter (mm)	Torque at ETC throttle shaft (N-m)	Material Bore / Valve
A	2	75	2.0	Metal / metal
B	7	54	2.5	Metal / metal
C	5	87	1.6	Metal / metal
D	1	54	1.8	Plastic / plastic
E	2	64	2.8	Plastic / metal

The differences in gap size (Figure 1) between the parts tested were judged to be insignificant compared to the volume of water used. Gap sizes ranged from 0.5 to 1.3 mm.

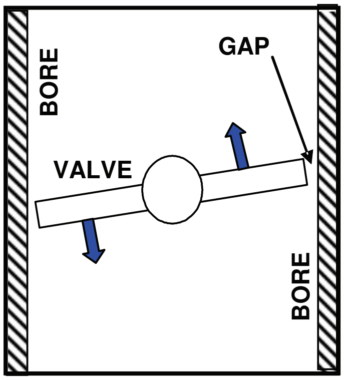


Figure 1. Simple diagram of a throttle valve

LABORATORY COMPONENT ICING TESTS – Initial laboratory testing was conducted with throttles cooled to -40°C as is customary for some vehicle throttle icing tests. These test results are not reported here because very little throttle sticking occurred due to the instantaneous freezing of the water on the bore surface. After careful inspection it was realized that only the throttles with water in the valve / bore gap had any significant level of sticking. Water must be allowed to flow into the gap in order to get levels of sticking similar to that seen in the vehicle tests.

It should be noted that PCV water vapor and throttle temperatures will initially be above ambient temperature in the vehicle during “soak icing”. As the environment cools, the water will condense on the valve, wick into the gap and freeze. The following two component icing tests incorporate this scenario into the test procedures to imitate vehicle icing.

Icing Test No. 1 – This laboratory test utilized a freezer set at a constant temperature of -15 °C and fixtures to hold the ETC-ACV parts in a stable, reproducible orientation. To reduce test variability, freezing rate, freezing temperature, water impurities and substrate surface cleanliness were controlled as much as possible [5]. A controlled amount of deionized water (50 microliters) at 25 °C was added using an adjustable volume pipette to the ETC-ACV at the bore / valve interface after cooling the part to -15 °C. The tip of the pipette was placed on the edge of the valve during application of the water. A photograph of a typical ice drop and part is shown in Figure 2. The size of the ice drop was approximately 5 mm wide by 3 mm high.

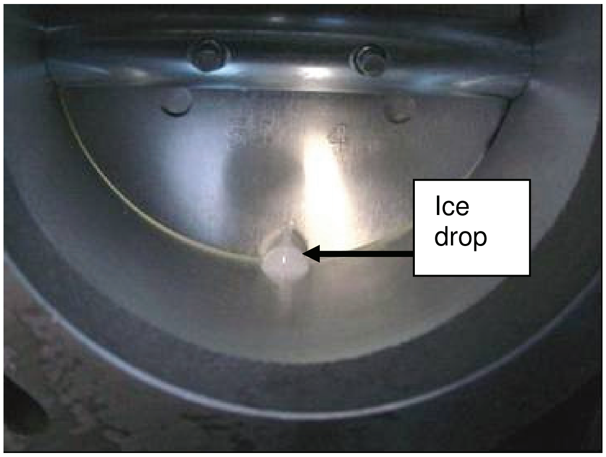


Figure 2. Typical location and appearance of ice from laboratory test No. 1.

Two variations of icing test No. 1 were performed to provide clues to the valve icing mechanism. The temperature of the water was modified in order to evaluate the effect of water wicking into the valve/ bore gap. Water at room temperature flowed easily into the gap; whereas, water at colder temperature did not.

- In variation 1, the deionized water was cooled to 5 ℃ before transferring it to the valve. This was done to reduce the wicking of the water into the valve / bore interface area.

- In variation 2, a piece of Teflon® [6] was placed between the water droplet and the valve, and the deionized water was cooled to 5 ℃. This was done to eliminate the wicking of the water into the gap.

Valve icing or sticking was measured using a computer controlled typical engine control module driver to record duty cycle required to close the valve. Maximum duty cycle needed to break the ice was measured. Seven parts of design B were tested. Results from icing test No. 1 were used to understand and evaluate the icing mechanism.

<u>Icing Test No. 2</u> – The electrical actuation of the valve to measure ice breakage in icing test No. 1 contributed to data variability due to part-to-part variation of the motor / gear train torque. In addition, greater than 100% duty cycle was needed in some tests to break the ice. For these reasons, icing test No. 2 was developed.

Icing test No. 2 was similar to icing test No. 1; however, 250 microliters of deionized water at 25 ℃ was used and the force to close the valve was measured using an Instron measurement system (Lloyd Instruments). The Instron was used in order to obtain actual force data that could be converted to torque. Force curves were obtained plotting extension or valve movement in millimeters from the default position vs. force in Newtons. Two hundred and fifty microliters of water was determined to give an acceptable range of forces for the 1 kilo-Newton load cell moving at a constant speed of 20 millimeters / minute. Water was added to the intake manifold side of the valve (engine side). A representative photograph is shown in Figure 3.

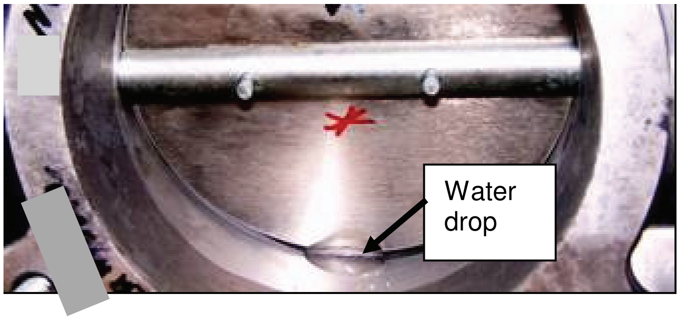


Figure 3. Typical location and appearance of ice from laboratory test No 2.

The force of the Instron was applied as close to the bore as possible, perpendicular to the shaft, to close the valve from the default position as shown in Figure 4. The force in Newtons measured by the Instron was converted to torque (Newton-meters) by multiplying the force (Newtons) by the distance (meters) from the center of the valve blade to the location of the Instron force. This conversion was made in order to compare test results with the actual torque available at the throttle shaft from the motor for each ETC-ACV.

Icing test No. 2 was used to evaluate icing potential for plastic and metal materials, bore size, effects of ETC-ACV inclination ("tip"), cleanliness of valve surface and effects of valve orientation.

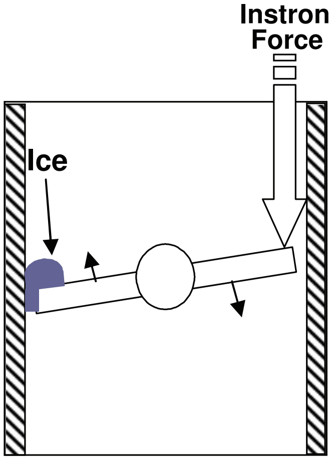


Figure 4. Location of ice and Instron force from laboratory test No. 2.

Icing test No. 2 repeatability – Two parts were tested six times by one operator to measure repeatability of laboratory icing test No. 2. Data is shown in Table 2. Based on this data the test method was considered acceptable for measuring valve sticking due to ice formation. The same operator was used for all subsequent tests reported in this paper.

TABLE 2: Icing Test No. 2 repeatability

	Maximum Torque for	Ice Break (N-m)
Test No.	Part C2	Part C3
1	7.2	3.8
2	5.1	3.9
3	6.6	4.3
4	6.3	3.0
5	5.4	3.9
6	7.6	2.9
Minimum	5.1	2.9
Maximum	7.6	4.3
Average	6.4	3.6
Std. Deviation	1.0	0.5

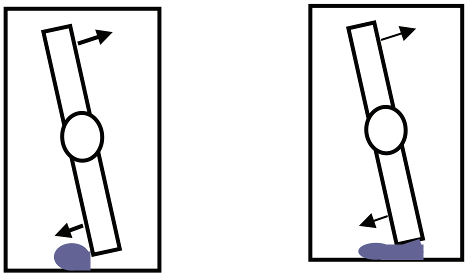
Icing test No. 2 sensitivity – In addition to repeatability, a good icing test method will also be able to differentiate between various ETC-ACV designs with a range of ice-break forces. 250 microliters of water was determined to be an optimum volume to cause ice-break forces in a reasonable and realistic range. Results from icing test No. 2, reported in the following sections, will show that the test is sensitive enough to detect differences between various part design features.

RESULTS AND DISCUSSION

The icing tests reported in this publication duplicate the location and relative amount of ice observed on actual vehicle throttle valves experiencing icing conditions. Using a laboratory bench test, as opposed to a vehicle test, allows the investigator to quickly and inexpensively compare product designs and investigate icing mechanisms. It was demonstrated that as little as 250 microliters of water, frozen in the correct location, can cause a level of valve sticking not overcome by ETC-ACV motors with industry standard torque capabilities.

ICING MECHANISM – Ice adhesion to the valve and bore surfaces was believed to be the primary cause of throttle icing or sticking. Data from studies done on ice adhesion on various substrate materials has been used to support design changes to throttle materials [5]. Ice adhesion tests have been used to evaluate coatings and plastic materials to reduce the surface tension and therefore theoretically reduce or eliminate the effects of icing [7, 8, 9]. However, based on the data from icing test No. 1, ice compression in the valve / bore gap, also referred to as the "wedge effect", was found to be the primary contributor to throttle valve sticking. Ice adhesion was found to be a secondary, minor contributor.

As can be seen in Figure 5, test results obtained with no water, with the Teflon, and with the water at 5°C were very similar. This was to be expected since in each case there was little to no water in the valve / bore gap. This was confirmed visually during the test. Some amount of sticking was observed that was attributed to the ice adhesion to the bore surface. When the water at 25 °C was added to the part at -15 °C, the water was able to wick into the valve / bore gap before freezing. Graph 1 clearly shows a significant increase in torque required to close the valve when the water is at 25°C. These results indicate that the contribution of ice adhesion to valve sticking is minor in this test compared to the contribution of ice compression at the valve / bore gap. The increase in torque is not due to simple adhesion of the ice to the bore or valve impeding the valve movement. Figure 6 shows a simple diagram depicting this conclusion. Experimental results with plastic ETC-ACV valves and bores, discussed later, also support this conclusion.



Low force for ice-break High force for ice-break

Figure 6. Simple diagrams showing valves with low and high ice-break forces.

BORE SIZE – To investigate the effect of bore size on icing, torque data was compared among part designs A, B and C. These 3 designs use metal materials for bore and valve construction. The maximum torque required to move the valve from the default position was recorded. The torque required to move the valve without ice was subtracted from these results. Data is shown in Figure 7. Averages of results were used from multiple runs for multiple samples of part designs A, B and C (metal valve / metal bore). In general, a larger bore size resulted in larger torque to close the valve. Larger variation in results for design C sample parts (largest bore) was observed. This variation may be due to differences in bore shape. Design C has a spherical bore shape compared to the other parts' cylindrical bore shape. The higher torque is expected for the larger bore because the force is acting at a longer moment arm. In addition, a larger radius of curvature of the bore could result in more surface area coverage by the ice in the valve/bore gap. Data from this study could be used to estimate the torque needed for specific throttle bore sizes.

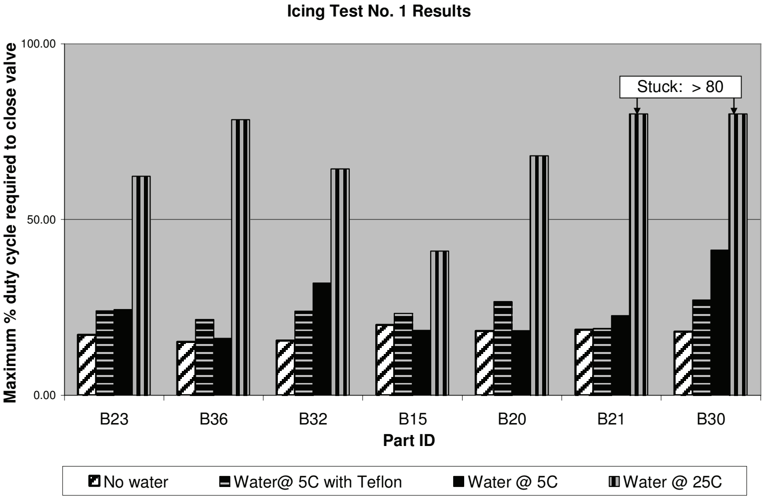


Figure 5. Results from icing test No. 1 for ETC-ACV design B. An increase in valve sticking was observed with water @25C due to wicking into the valve / bore gap.

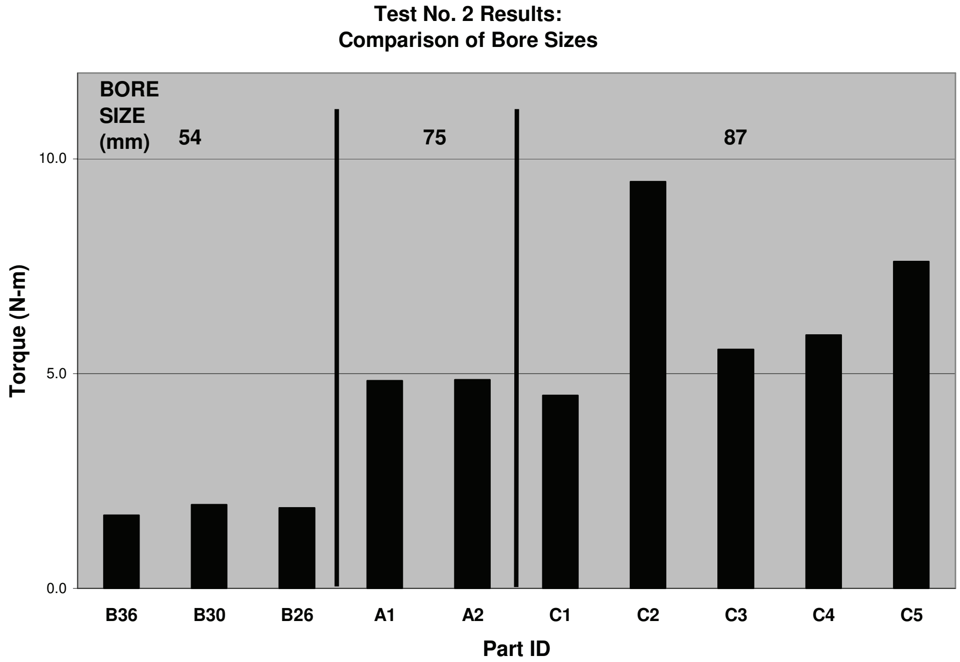


Figure 7. Comparison of ice-break torque for different bore sizes.

PLASTIC VS. METAL MATERIALS – Tests were performed using icing test No. 2 to compare the torque results from parts with plastic and metal valves and bores. Parts with similar bore sizes were compared. Results are summarized in Figure 8. Duplicate icing tests were performed on the metal/metal parts. Four separate icing tests were performed on the parts containing plastic valves and/or bores. No improvement was demonstrated with plastic components, even though these materials would have lower ice adhesion forces from lower surface tension compared to the metal parts. These results support the icing “compression” or “wedge effect” theory discussed in the previous section. If ice adhesion to the valve or bore was a major contributor to the throttle valve icing phenomenon, a reduction in torque would have been measured compared with the results from the metal / metal parts.

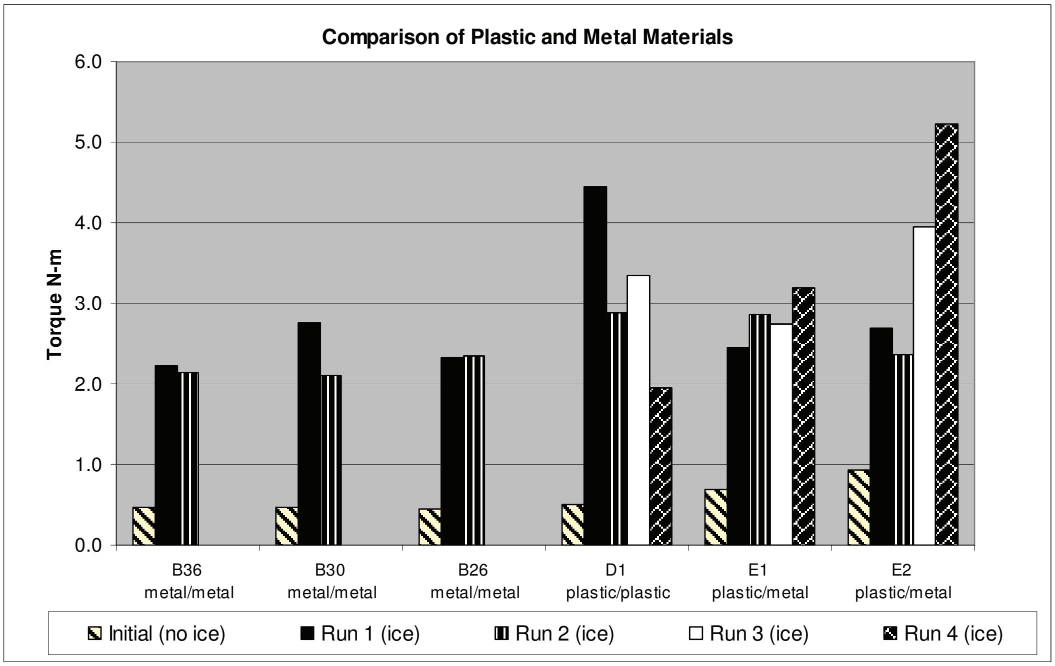


Figure 8. Comparison of torque required to break ice for plastic and metal materials

PART INCLINATION (TIP) – To investigate the effect of valve tip, a fixture was designed to hold the ETC-ACV at different tip angles (10, 20 and 30 degrees). Only metal bore/ metal valve parts were tested. Valve inclination is shown in Figure 9.

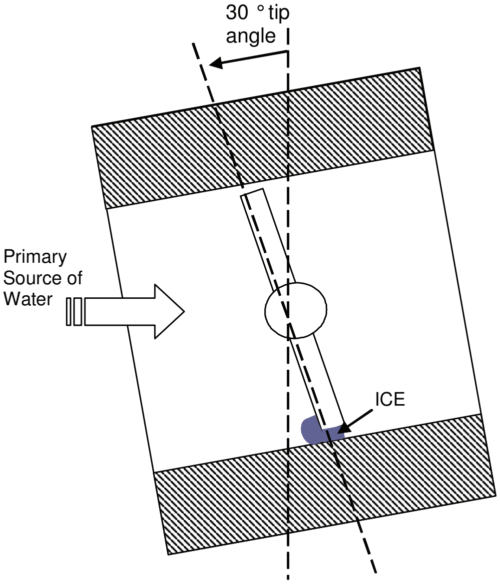


Figure 9: diagram showing ETC-ACV tip angle

The results of this test were more variable than obtained with the original (0 degree tip angle) test due to the fact that variable amounts of water visibly moved away from the valve edge. However, even at a 30 degree tip angle, enough water wicked into the small gap between the cold (-15℃) valve and bore to result in a closing torque increase. Results for parts C2 and B36 are shown in Figure 10 and a typical Instron force curve is shown in Figure 11.

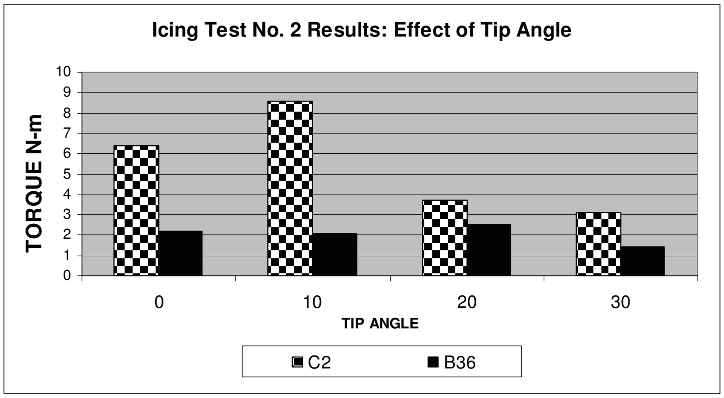


Figure 10. Ice-break torque vs. tip angle- parts C2 and B36

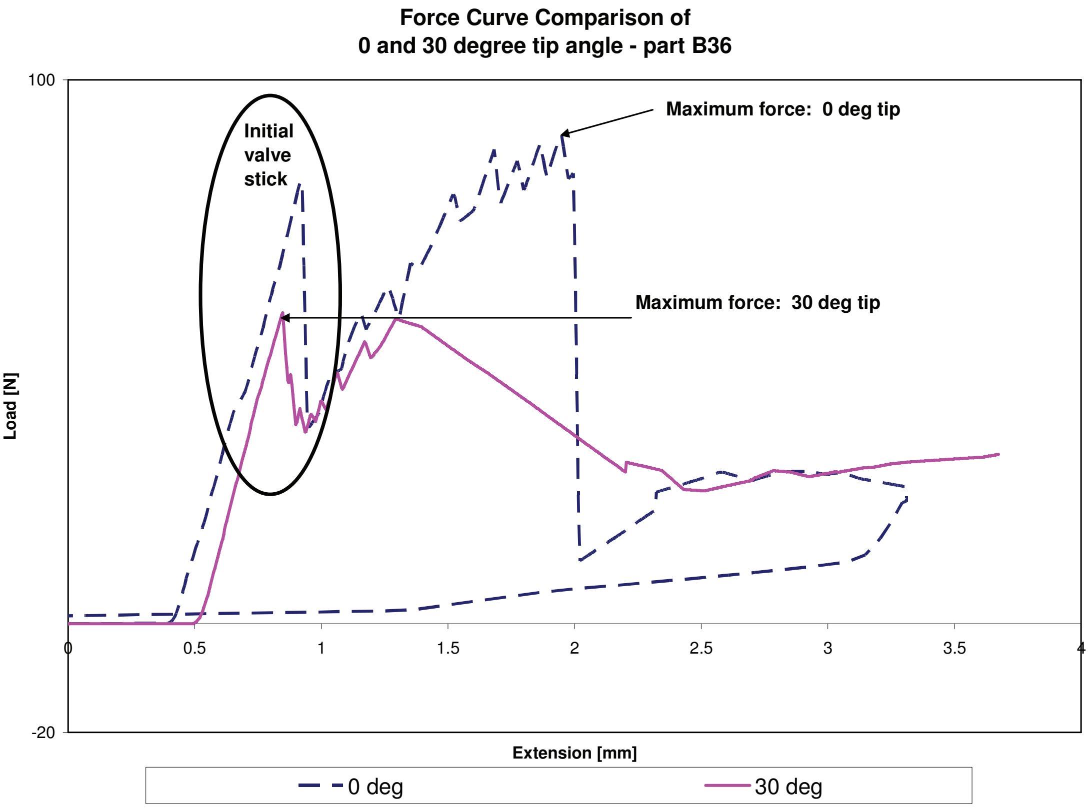


Figure 11. 0 and 30 degree tip angle force curves for iced part B36

SURFACE CONTAMINATION – Due to the location of the ETC-ACV in the engine, it is likely that a thin layer of oil from the crankcase will be present on the surfaces of the valve and bore during use on the vehicle. This would reduce the surface energy of the valve and bore surfaces, thus reducing the ice adhesion force between the ice and the throttle bore/ valve. Previous theories linking ice adhesion force to ETC-ACV valve icing would therefore predict a small probability of icing occurrences during use on the vehicle [9]. The fact that icing is a well-known and prevalent problem in the field contradicts the adhesion theory and gives support to the icing mechanism detailed in this publication.

A test was conducted using icing test No. 2 and parts that were contaminated with a thin layer of light mineral oil. Again, the results of this test were more variable than the original test with clean parts due to variable amounts of water wicking into the valve/ bore gap (confirmed visually). The level of torque increase due to icing was reduced when the oil was present; however there was still evidence of valve sticking due to ice formation. Test results for parts B36 and C3 are shown in Figure 12. A typical Instron force curve showing the ice-break force for part B36 is shown in Figure 13. Figure 13 illustrates that with the oiled surface, throttle icing can still occur with a relatively small volume of water present (250 microliters).

These results support the conclusion that ice compression in the gap, not ice adhesion, is the major contributor to valve sticking. It is important to note that the oiled surface would represent a best-case field exposure condition with no carbon or other deposits present on the surface to trap water.

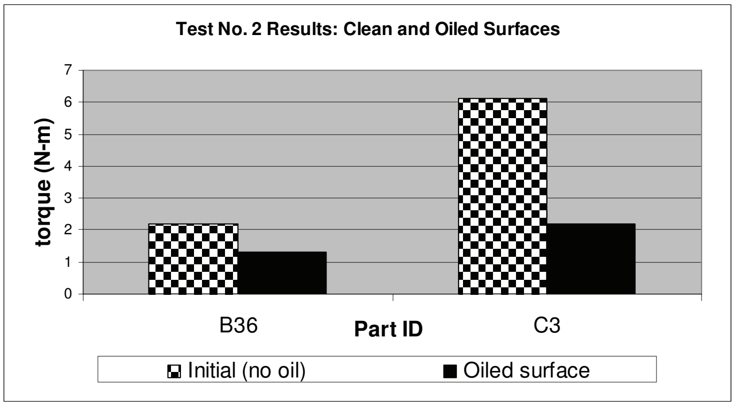


Figure 12. Comparison of ice-break torque for clean and oiled surfaces

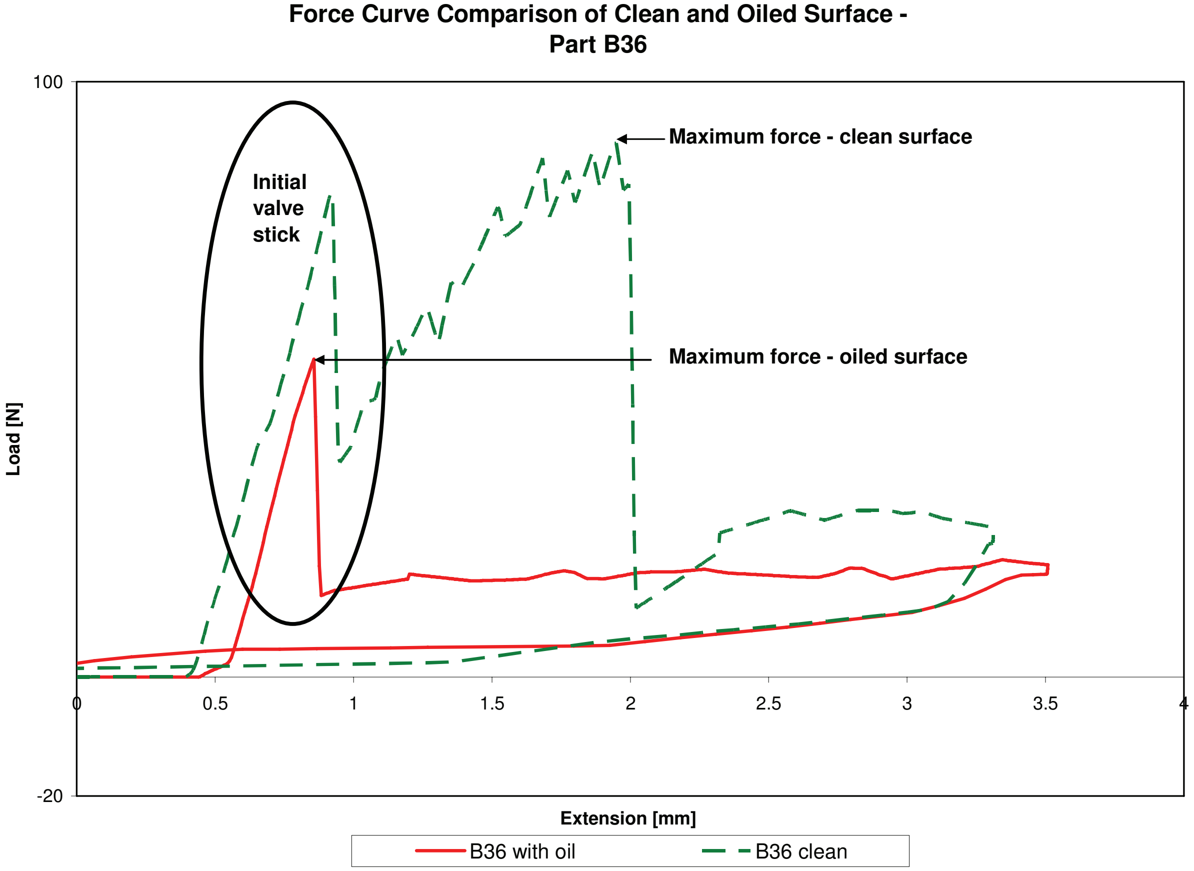


Figure 13. Instron force curves of iced parts with and without light mineral oil surface contamination

PART ORIENTATION – Part orientation refers to the direction in which the valve is rotated from the default position. The valve could be installed on the engine so that the initial rotation is away from the primary source of moisture, or towards the primary source of moisture. In this study, parts were tested in both orientations to confirm the theory that the least amount of compressive stress will occur if the part rotates AWAY from the primary source of moisture. Two parts of design C were tested six times. Results are shown on Figure 14. The average torque for valve rotation toward the ice was 6.4 ± 1.0 N-m torque. The average torque for valve rotation away from the ice was 3.6 ± 0.5 N-m torque, a 44% improvement. Rotation of the valve away from the primary water source decreases the level of valve sticking due to ice formation in icing test No. 2.

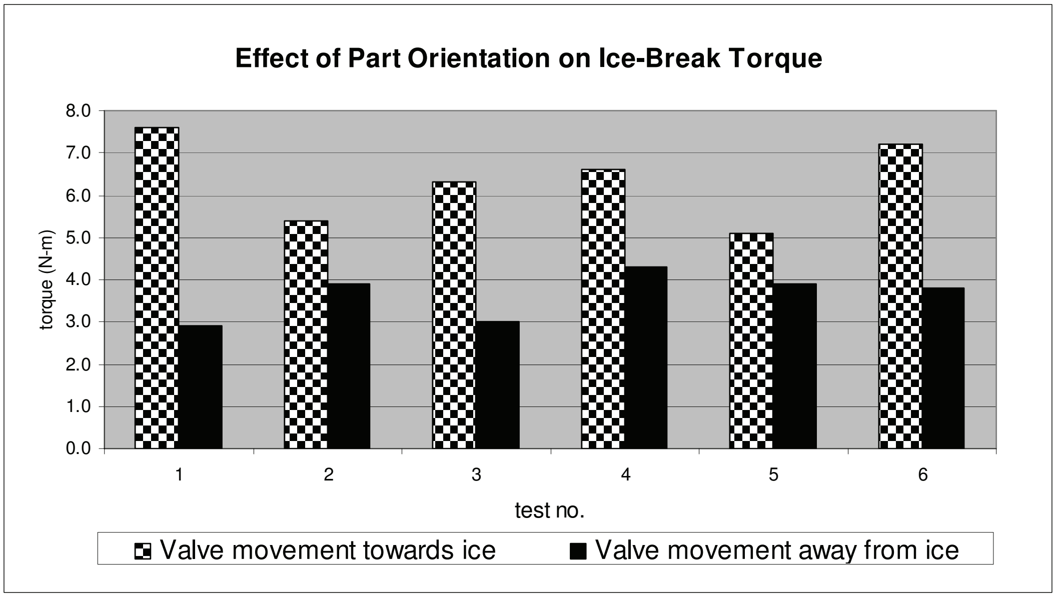


Figure 14. Comparison of ice-break torque for two rotation directions.

CONCLUSIONS

The following conclusions can be made based on the data presented in this publication:

1. Contrary to many reports and theories in the industry, the icing test results summarized in this paper indicate that ice adhesion to the surfaces of the ETC-ACV valve and bore is a minor contributor to the valve icing phenomenon. The major contributor to the icing problem is the compressive stress of the ice at the gap between the valve and bore.

2. Volumes of water as low as 250 microliters can cause a significant increase in valve closing torque when frozen in the gap between the valve and bore.

3. Use of plastic materials for the bore and valve construction did not reduce the ice-break force in the experiments detailed in this paper.

4. Tipping the part toward the primary source of water and/or orienting the part so that the initial movement of the valve is away from the primary source of water may significantly reduce, but not necessarily eliminate, the risk of throttle icing.

5. Oil contamination on the surfaces of the ETC-ACV valve and bore from PCV can reduce, but will not necessarily eliminate, throttle icing. Since oil contamination would theoretically reduce the force of ice adhesion, these results support the theory that compressive stress of the ice in the valve / bore gap is the primary contributor to valve icing.

6. Industry standard torque specifications for throttle motors are generally bore size independent. Based on the data from this study, the torque needed for ice-break varies with bore size. This information should be considered when throttle motor torque requirements are specified.

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