Engine Rapid Shutdown: Experimental Investigation on the Cooling System Transient Response

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Experimental measurements have been taken on a production four-cylinder, multipoint (fuel) injection spark-ignition engine, 1.2 dm^3 displacement with a four-valve per cylinder aluminum head, and a 60 kW at 5500 rpm rated power. The aim of the investigation was to understand the behavior of the cooling system of a small automotive engine, which was operated for a prolonged period at high speed under full or part load, then brought to idle for a short period and finally shut down. In this study, the effects of different loads, idle operation time, and lengths of the engine-radiator piping were analyzed. In particular, experimental tests were carried out with the engine running at 4000 rpm under different brake mean effective pressure values in the range 496 to 1133 kPa. In all experimental tests the engine was brought to idle in 5 s, and measurements were repeated for different values of the idle operation time ranging from 1 s to 80 s. Test data of coolant conditions and metal temperature at 26 points of the engine head and liner were recorded. The cooling circuit was instrumented with transparent tubes at the radiator inlet and photographs of the vapor phase moving to the radiator were taken during experimental tests. The volume of leaked coolant as a function of time was also measured. Additional tests were carried out to evaluate the effects of different lengths of the engine-radiator piping on the after-boiling phenomenon. Finally, in order to make the results applicable also to nonautomotive engines, measurements were repeated without the standard cabin heater and the associated piping. The investigation results show that as the engine is shut down and coolant flow stops, the head metal may be hot enough to vaporize a fraction of the coolant contained in the cylinder head passages, causing the pressure within the cooling circuit to rise above the threshold value of the radiator cap pressure valve and, consequently, an important quantity of the coolant to be expelled.
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Keywords: engine cooling system, thermal transient response, internal combustion engine, after-boiling, engine shutdown

1 Introduction

In the past decade, the evolution strategies of the automotive industry have been addressed to providing engines with increasing power levels and compact design. This trend has challenged engine manufacturers to re-evaluate the role that the cooling system plays in the efficiency, emissions, and reliability of the ICE and to search for innovative solutions for thermal energy management. The target is reduced fuel consumption and emissions with optimized coolant flow, optimized engine temperature, quick warm-up of engine at cold start, enhanced passenger comfort, and engine durability [1–5].

In the context of durability testing, special consideration is reserved to the behavior of the cooling system during transient conditions. In fact, cooling circuits in most present liquid-cooled cars include only a centrifugal pump driven by a belt connected to the crankshaft, which circulates coolant while the engine is running, but no coolant circulation is guaranteed as the engine is shut down. As a consequence, when the engine is stopped after a prolonged time of high load operation, the coolant temperature may rapidly increase, and a fraction of the coolant eventually vaporizes as a result of flow stoppage. If the vaporized mass of coolant is non-negligible, the pressure within the cooling system rises up to the level that causes the opening of the radiator cap pressure valve and part of the coolant leaks out. This phenomenon, which is often called after-boiling, is much more likely to occur in small engines, which more probably are operated at high load and are also shut down frequently. The sight of leaked coolant is in itself a very unpleasant experience for the user and, moreover, if the quantity of expelled coolant is significant, the engine cannot be restarted until the right coolant level is restored.

The rapid shutdown of an engine from a condition of high metal temperature also produces rapid metal temperature variations, which can cause significant temperature spatial gradients and material stress. Under particularly severe conditions, cylinder head gasket splitting failure may be observed. Engine manufacturers are therefore interested in avoiding the occurrence of the phenomenon and severe thermal-stress tests are routinely carried out during engine development. This paper presents a large number of tests carried out on this matter at the Department of Mechanical Engineering of the University of Calabria (Italy) in cooperation with ELASIS S.C.p.A. (Pomigliano D'arco, Italy) on a production four-cylinder 1.2 dm^3 displacement spark-ignition (SI) engine [6–8].

2 Experimental Apparatus

A small production four-stroke SI engine was used for this testing. The engine displaces 1.242 dm^3 in four in-line cylinder with

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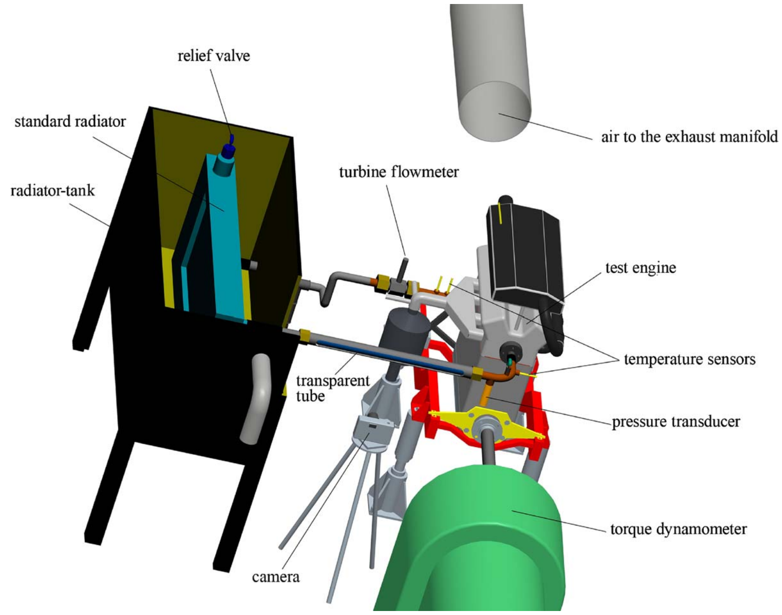
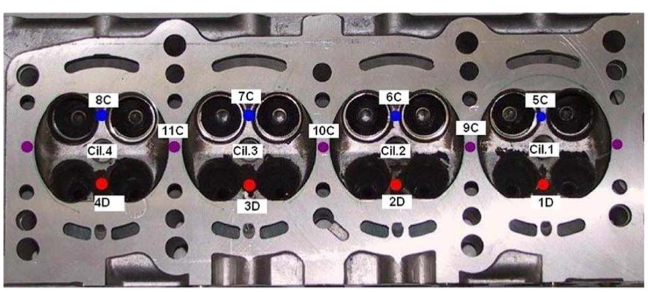


Fig. 1 Schematic of the engine test-bed

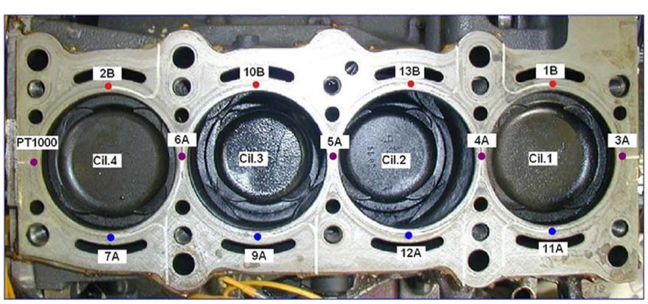
a four-valve per cylinder aluminum head and a 60 kW at 5500 rpm rated power. The engine was installed on a Borghi&Saveri FE 260-S eddy current engine torque dynamometer (capacity of 260 hp at a maximum of 12,000 rpm) equipped with an actuator for remote control of throttle position.

The cooling circuit was set up with minimal modifications regarding the layout used in a production vehicle, including the heater for car passengers' comfort. The only deviation is the standard radiator immersed in a tank filled with water, whose temperature was controlled by means of flowing cool water in order to keep engine inlet coolant temperature constant within a $\pm 1^{\circ}\mathrm{C}$ error band. A digital proportional, integral, differential (PID) regulator was used for controlling the cool water flow rate entering the radiator-tank, providing an output voltage to pilot a solenoid water flow control valve (Fig. 1).

Values of the metal temperature of the cylinder block and cylinder head were measured at various locations (Fig. 2) with k-type thermocouples located in the metal, within a small distance (~ 1 mm) from the gas/wall interface [9]. The coolant pressure, at the location shown by Fig. 1, was measured with a Tekkal strain gauge pressure transducer, with an accuracy of ± 0.05 bar maximum. Coolant temperatures were measured using PT100 type temperature sensors installed at the engine inlet and outlet. Coolant volume flow rate was measured using a Flow Technology's FT-16 turbine type flowmeter, with a repeatability of $\pm 0.05\%$. An optical access was also installed in the cooling circuit near the radiator inlet to observe visually the coolant flow pattern during experimental tests. All tests were performed with a 50/50 (% by mass) mixture of water and commercially available ethylene glycol. A scheme of the engine test-bed and the experimental apparatus is shown in Fig. 1.



Cylinder head metal	
Group name	**Thermocouples**
Exhaust valves bridge	1D, 2D, 3D, 4D
Intake valves bridge	5C, 6C, 7C, 8C
Between cylinders	9C, 10C, 11C



Cylinder block metal	
Group name	**Thermocouples**
Exhaust manifold side	1B, 2B, 10B, 13B
Intake manifold side	7A, 9A, 11A, 12A
Between cylinders	3A, 4A, 5A, 6A

Fig. 2 Cylinder head and cylinder block thermocouple locations

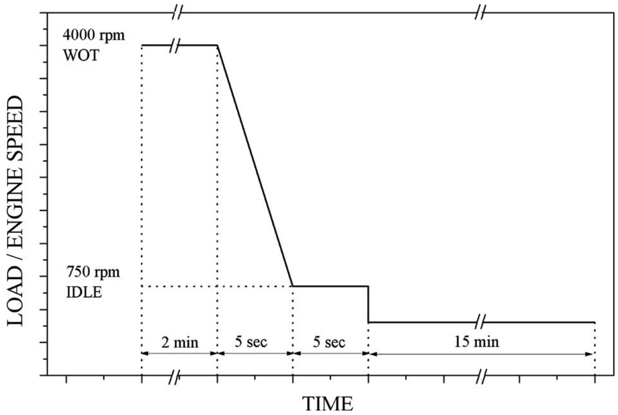


Fig. 3 Load and engine speed variation during a "rapid shutdown" test at WOT

3 Test Procedure

The experimental procedure of the "rapid shutdown" tests is shown in Fig. 3. The engine was operated at 4000 rpm at the brake mean effective pressure (bmep) values specified in Table 1 for a long enough time to stabilize metal and coolant temperatures. Data were recorded for 2 min in this condition and then in 5 s the engine was brought to idle. The idle operation was maintained for a time interval Δt_{min} (Table 1) and then the engine was stopped. In addition to the transition to idle and the idle operation, data were recorded for 15 min after engine shutdown (Fig. 3) at a sampling rate of 2 Hz.

Two sets of experiments were carried out for different value of Δt_{min} and initial load (Table 1). For evaluating the effect of idle operation time, a first set of experiments was conducted at wide open throttle (WOT), while idle operation was maintained from 1 s to 1 min and 20 s. A second set of experiments was carried out at a fixed 5 s idle operation time for different values of the initial load (bmep in the range 495–819 kPa, Table 1). The 819 kPa bmep represents the typical value to drive a small production vehicle on a level road at a steady speed (130 km/h); the 495 kPa bmep is the limit value, which does not cause after-boiling for any idle duration.

The common operating conditions shown in Table 1 and the baseline idle operation time of 5 s were judged, in agreement with the engine manufacturer, the most meaningful for investigating the after-boiling phenomenon.

Finally, additional tests were performed with different lengths of the piping between the engine outlet and the radiator inlet.

Table 1 Common operating conditions for rapid shutdown tests: (a) operating conditions for rapid shutdown tests at WOT and (b) operating conditions for rapid shutdown tests at part load

Parameter	Description	Value
N_{max}	Engine rotational speed at full/part load	4000 rpm
N_{min}	Engine rotational speed at idle	750 rpm
Δt_{max}	Duration of data acquisition during full/part load operation	2 min
Δt_{var}	Duration of the full/part load-idle transition	5 s
Δt_{off}	Duration of data acquisition after engine shutdown	15 min
(a) $bmep_{max}$	Brake mean effective pressure at WOT	1133 kPa
Δt_{min}	Time interval of idle operation	1–80 s
(b) $bmep_{max}$	Brake mean effective pressure at part load	495–819 kPa
Δt_{min}	Time interval of idle operation	5 s

4 Experimental Results and Discussion

The operating conditions that mainly affect the after-boiling phenomenon are time interval of idle operation, initial load (bmep), and length of the piping between the engine outlet and the radiator inlet [6,7]. In the following paragraph, experimental results of rapid shutdown tests starting from the WOT condition are illustrated in detail for the case of a 5 s duration of the idle operation, with the standard length of cooling circuit used in a production vehicle. This case will be used as the baseline case for the after-boiling phenomenon. The effect of changes of the operating conditions will be discussed in Secs. 4.2–4.4 and differences will be emphasized in comparison to the baseline case.

4.1 Baseline Case. Figure 4 shows the time history of coolant temperature and pressure at engine outlet and the temperature evolution of the metal at the measuring points in the engine head and in the cylinder block, for the case of 5 s of idle duration initial load at WOT standard length of cooling circuit. Figure 4 also depicts the time abscissa at which the engine is shut down and the time interval during which coolant leakage occurs. In Fig. 5 the coolant conditions and the temperature at two points in the cylinder head and cylinder block are shown in more detail (exhaust valve bridge: hottest point—location 1D in Fig. 2; metal of cylinders block: coldest point—location 11A in Fig. 2), with the time scale enlarged in the most interesting time interval.

The analysis of tests results together with the visual observation of the phenomenon through the optical access at engine outlet allows one to identify the following data points on the curves of Fig. 5: a is the start of the high load-idle transition, b is engine shutdown, d_1 is the start of air leakage through the relief valve, d_2 is the end of air leakage, f_1 is the start of coolant leakage through the relief valve, f_v is the inlet of vapor phase inside the radiator, and f_2 is the end of coolant leakage.

Coolant pressure and temperature during full load operation are essentially constant and so is the metal temperature at any measuring point. Starting from the time abscissa 2, during the 5 s transition to idle and the subsequent 5 s of idle operation (stretch a-b in Fig. 5), coolant flow rate and pressure suddenly diminish due to the lower pump rotational speed. Coolant temperature at engine outlet therefore rises due to a longer residence time within the engine, where some nucleate boiling of the coolant within the engine eventually occurs. Also the metal temperature of both engine head and cylinder block rapidly decreases during this period (Fig. 5(b)).

After engine shutdown (point b) the coolant flow rate also stops, while the head temperature is still quite high (about 150°C, well above coolant saturation temperature ~129°C). Consequently, part of the coolant vaporizes within the engine head. This gives rise to a pressure increase and pushes the fluid out of the engine toward the radiator: A temperature increase at the engine outlet is therefore recorded. At the same time, the metal temperature of the head steadily diminishes, while the temperature of the part of the engine block closer to the coolant entrance, after reaching a minimum, starts to increase (Fig. 5(b)) as a result of conductive heat transfer from the warmer engine block parts. Three different phases can be identified on the curves in Fig. 5.

4.1.1 Phase A: Air Compression. The sudden heat transfer from the high temperature head metal to the coolant contained in the cylinder head passages causes a rapid increase in coolant temperature and pressure. At the same time, a fraction of the coolant eventually vaporizes and this causes the pressure in the cooling circuit to rise above the level which would be reached owing to heat transfer alone. In this phase, the air contained in the radiator expansion tank and in the air-pockets in the cooling circuit (radiator and heater-core) is compressed to a small fraction of its initial volume. At the end of this phase (point d_1, Fig. 5), the pressure

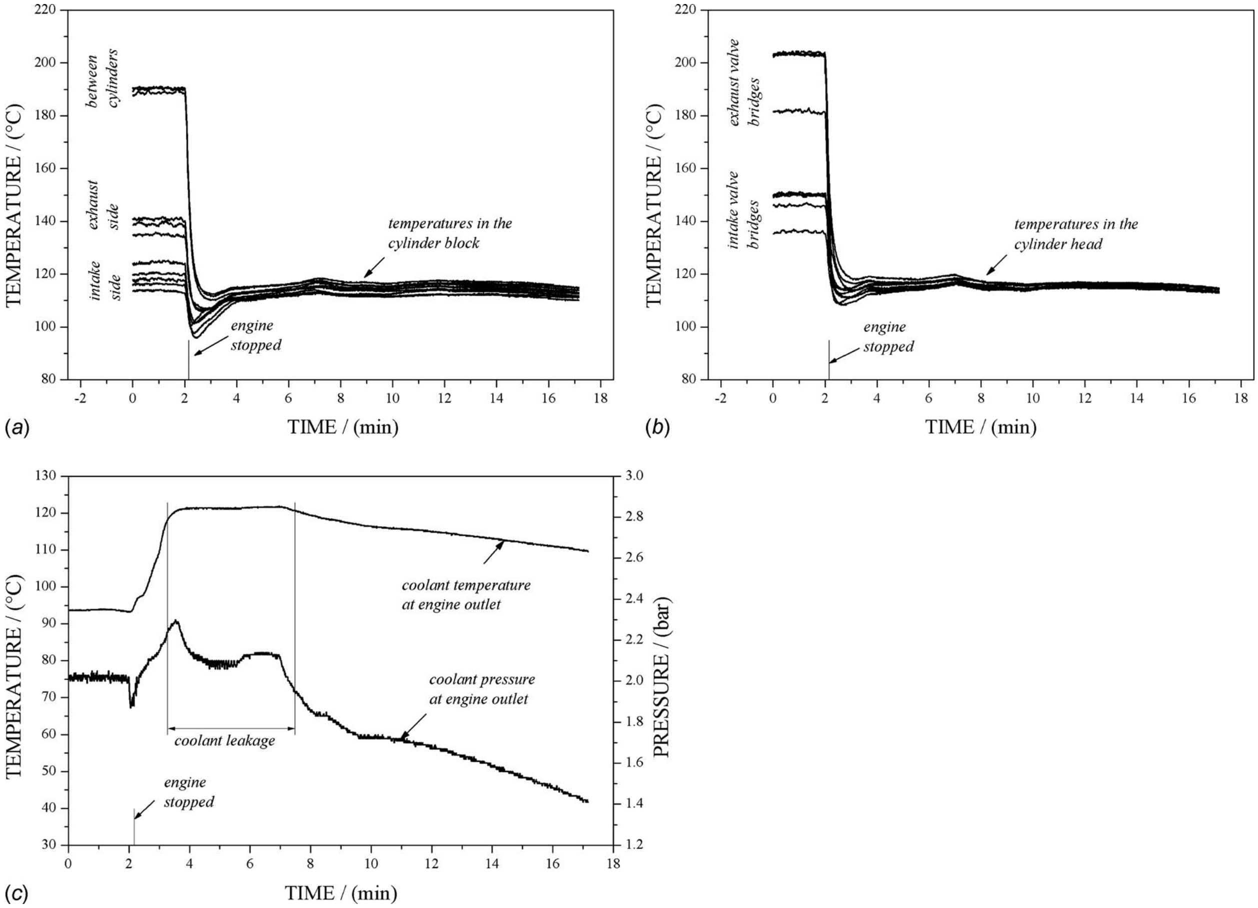


Fig. 4 **(*a*) Temperature evolution in the cylinder block and (*b*) in the engine head. (*c*) Time history of coolant pressure and temperature at engine outlet. Baseline case: time of idle operation 5 s; initial condition at WOT; standard length of cooling circuit.**

within the cooling system rises up to the level, which causes the opening of the radiator cap pressure valve (normally 2.0–2.15 bar).

4.1.2 Phase B: Air Leakage. As the pressure rises above the threshold value of the radiator cap pressure valve, air in the radiator expansion tank starts to be expelled (point d_1, Fig. 5). At this stage the pressure in the cooling system still increases, mainly due to vapor production which occurs in the cylinder head passages; a residual temperature gradient between the head metal and coolant, however, allows the heat transfer to continue. During this phase the average coolant temperature within the engine head is the average temperature that will be measured at the engine outlet some time after, i.e., $\sim 120°$C. Local coolant temperature may be of course quite higher. On the basis of ad hoc experimental tests a saturation pressure of 2.45–2.50 bar was estimated [8], well above the coolant pressure (2.0–2.2 bar) measured during this phase. Coolant vaporization therefore definitely occurs. The pressure gradient between the engine head and the radiator forces the fluid to move: This is recorded by a pressure and temperature increase at the engine outlet (stretch d_1-d_2, Fig. 5). At point d_2 the air leakage phase stops and the radiator expansion tank becomes completely full of liquid, as was observed directly at the test rig.

4.1.3 Phase C: Coolant Leakage. At point f_1 the pressure is still above the threshold value of the radiator relief valve and the coolant starts to be expelled. At this stage, the pressure within the cooling system initially increases due to vapor production. As the effect of volume reduction owing to the leaked fluid becomes predominant over the effect of vapor production, the pressure first stops increasing and then starts to decrease. The temperature difference between the metal and coolant now becomes negligible, and no more heat transfer from the head metal to the coolant can occur during this phase. When the vapor phase reaches the radiator (point f_v, Fig. 5), a condensation of part of the vaporized mass of coolant occurs and the pressure in the cooling circuit quickly keeps diminishing due to the losses of vaporized mass. The inlet of vapor phase inside the radiator was observed visually through the stretch of transparent tube (see photographs in Fig. 5).

Finally, at point f_2 the pressure in the cooling circuit reaches the value, which causes the closing of the radiator cap relief valve, and the coolant leakage stops; from this point the refrigerant cools in the form of stagnant vapor at the engine outlet.

4.2 Effect of Idle Duration. The behavior of the cooling system changes if the time of idle operation is significantly prolonged. Experiments were performed using different values of the time interval of idle operation $\Delta t_{\min}$, respectively, 1 s,10 s, 45 s, and 80 s, in addition to the established baseline value of 5 s. Figures 6 and 7 show the time history of the coolant pressure and temperature at engine outlet and the evolution of the metal temperature, for the case of 80 s of idle operation (this represents the limit time in order to avoid, with the engine operating at conditions described in Table 1, the occurrence of the after-boiling phenomenon).

The data points *a* and *b* marked out on the curves in Fig. 7 assume the same meanings of the baseline case. The conditions during the full load operation, the transition to idle and the first 5 s of idle operation, obviously do not differ from the one presented

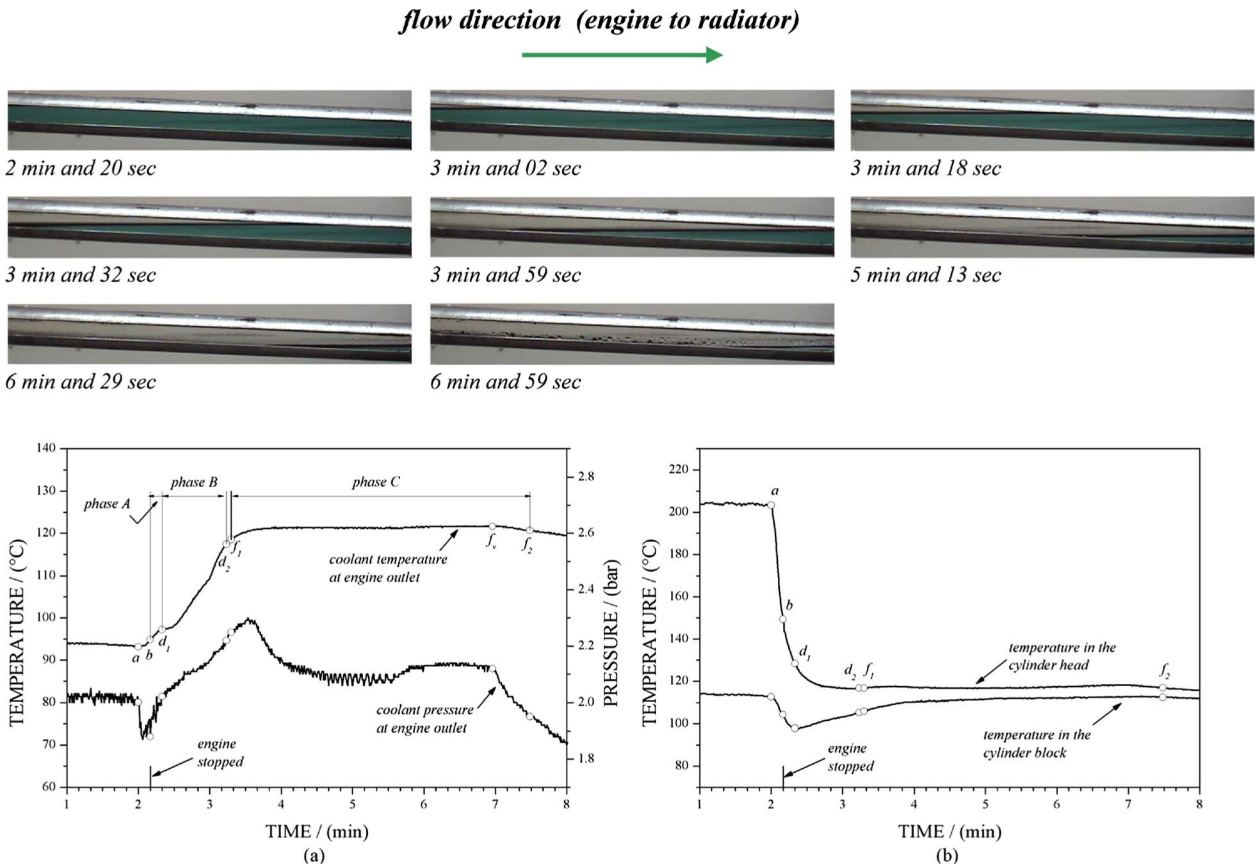


Fig. 5 Top, sequence of photographs of coolant flow from engine outlet to radiator inlet taken with transparent piping. Bottom, details of the case in Fig. 4 during the most rapidly varying part of the thermal evolution following a rapid shutdown. (*a*) Coolant pressure and temperature; (*b*) head and cylinder block temperature at two representative measuring points. Times of the photographs refer to the time abscissa.

in Fig. 5. After point a during the 5 s of transition to idle, a rapid pressure drop is recorded at the engine outlet, as a consequence of the quick reduction in the pump rotational speed, while during the 80 s of idle operation, coolant temperature and, consequently, pressure at the engine outlet decrease (stretch $a-b$, Fig. 7) due to the longer transit time of coolant through the radiator. During this period, also the metal temperature steadily diminishes, so that the values at engine shutdown (point b, Fig. 7) are significantly lower than the corresponding values in Fig. 5.

However, the coolant pressure in the cooling circuit at point b is lower then the coolant saturation pressure corresponding to the metal mean temperature ($\sim 120°C$): This gives rise to some vapor production of coolant inside the head passages; at the same time, the temperature gradient between metal and coolant allows heat transfer to continue. Both these effects, at this stage, cause the pressure in the cooling circuit to increase after point b; however, results of calculations, to be published shortly, show that the second contribution is more relevant. Also coolant temperature at engine outlet increases, with a delay owing to the distance between the engine outlet and the location of thermoresistance in the cooling circuit. The air in the radiator expansion tank is now moderately compressed, but no leakage occurs because the pressure in the cooling system stays below the radiator-cup relief valve threshold value.

The analysis of the two cases previously described, respectively, the baseline case of 5 s of idle operation and the case of 80 s of idle operation exhaustively reflects also the other investigated cases of duration of the idle operation of 1 s, 10 s, and 45 s.

The volume of spilled coolant and the delay of leakage start after engine shutdown are reported in Fig. 8. The phenomenon is characterized by a considerable variability, but it is clear that the volume of leaked coolant decreases and the start of leakage is delayed as the idle operation is prolonged. If the engine is shut down after 1 s only of idle operation, the coolant leakage starts about 0.5 min after engine shutdown, and the volume of spilled coolant is about 1 l. The limit time to observe coolant leakage was found for an idle duration of about 45 s: In this condition a reduced quantity of coolant of about 0.4 l was lost through the radiator relief valve. Results in Fig. 9 refer to further tests carried out with the standard cabin heater and the associated piping removed, in order to make the results applicable to non-automotive engines.

4.3 Effect of Initial Load. Engine load affects the heat flux to the different surfaces of the combustion chamber and, consequently, the wall temperature distribution [9]. By reducing engine load, also the metal temperature is lower, especially at locations, such the valve bridge and the region between the exhaust valves of adjacent cylinders, where maximum temperatures occur as consequence of the higher heat flux and the difficulty of cooling. Mainly owing to reduced metal temperature, the behavior of the cooling system changes as the initial load condition decreases.

Several experiments were repeated under the conditions described in Table 1, varying the brake mean effective pressure in the range 495–819 kPa. In all experiments the baseline value of 5 s of idle operation before engine shutdown was maintained (Table 1). The aim of the investigation was to analyze whether the after-boiling phenomenon may occur also with the engine initially operated at normal driving conditions.

Figures 10 and 11 show a detail of the coolant conditions and of the temperature at the two already defined points in the cylinder head and cylinder block (exhaust valve bridge: hottest point—

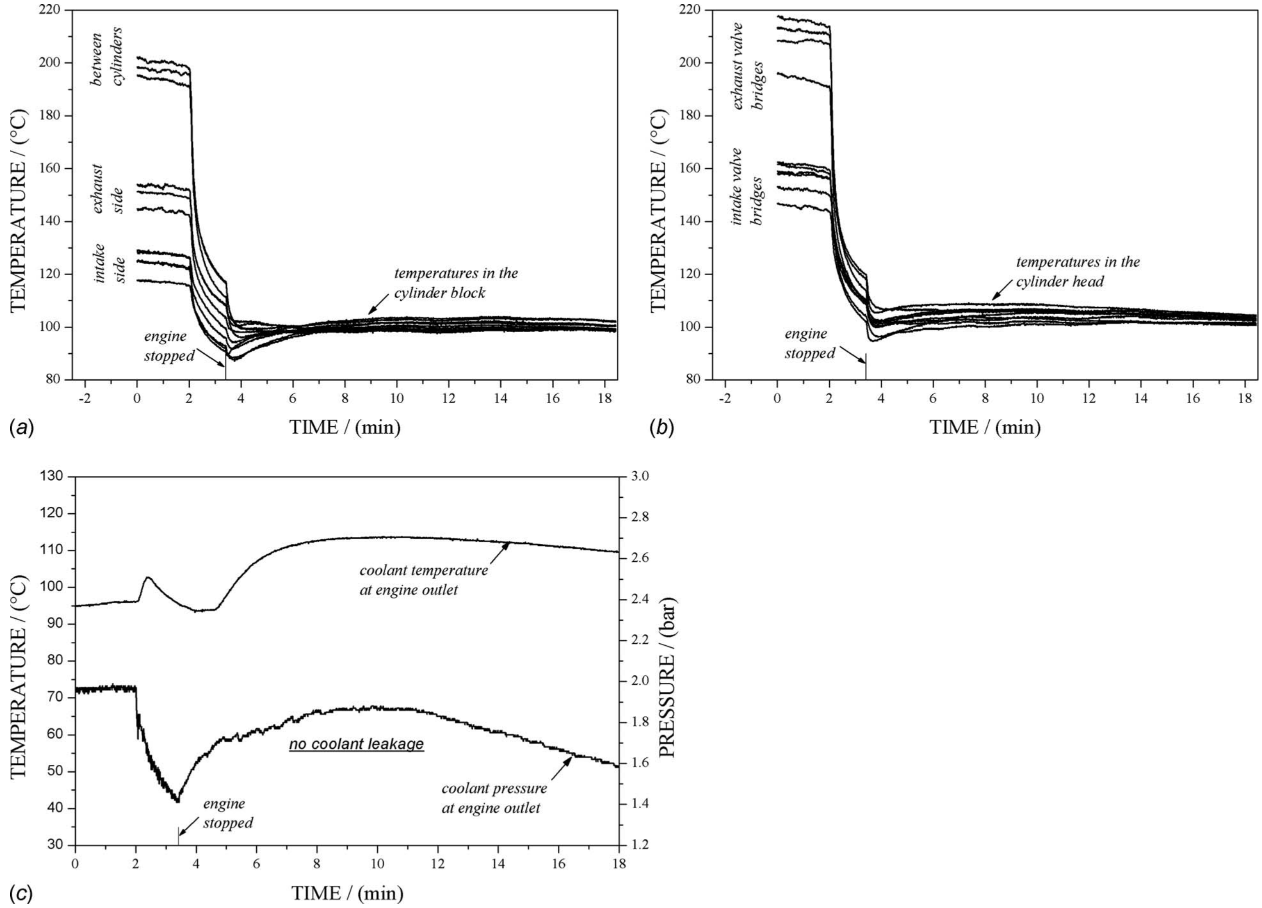


Fig. 6 (*a*) Temperature evolution in the cylinder block and (*b*) in the engine head. (*c*) Time history of coolant pressure and temperature at engine outlet. Prolonged time of idle operation: 80 s; initial load at WOT; standard length of cooling circuit.

location 1D in Fig. 2; metal of cylinders block: coldest point—location 11A in Fig. 2) for two tests conducted at initial load conditions corresponding, respectively, to 819 kPa and 495 kPa of bmep. The case of 819 kPa bmep value (Fig. 10) corresponds to the power required to drive a typical vehicle equipped with the test engine on a level road at a steady speed of 130 km/h; the case of 495 kPa bmep value (Fig. 11) refers to the maximum load which guaranties that no after-boiling phenomenon occurs.

The three different phases *A*, *B*, and *C* and data points *a*, *b*, d_1, d_2, f_1, and f_2 have the meaning defined in Sec. 4.1.

For the case of 819 kPa bmep, all these phases of the phenomenon still occur (see Fig. 10), and after the engine is shut down the coolant leakage starts about 1.5 min after engine shutdown time, and the volume of spilled coolant is about 0.6 l. On the contrary for the case of 495 kPa bmep, metal temperature is quite low, only phases *A* and *B* may be identified, and no leakage occurs.

The volume of spilled coolant and the delay of leakage after engine shutdown are reported in Fig. 12 for all the investigated bmep values. The phenomenon is characterized by a considerable variability, but it is clear that the volume of leaked coolant decreases, and the start of leakage is delayed as the initial load is decreased.

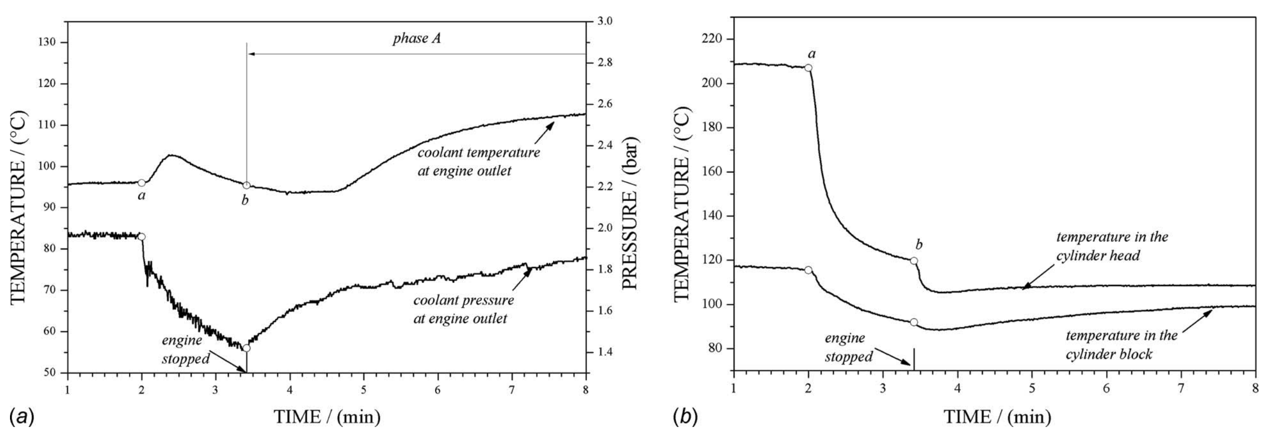


Fig. 7 Details of the case in Fig. 6 during the most rapidly varying part of the thermal evolution in the case of a prolonged idle operation. (*a*) Coolant pressure and temperature; (*b*) head and cylinder block temperature at two representative measuring points.

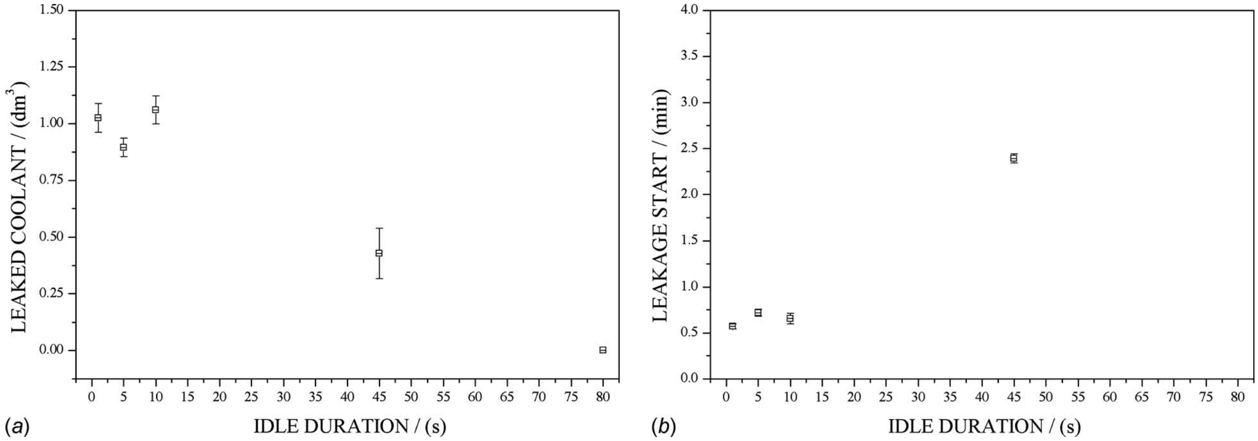


Fig. 8 (*a*) **Volume of the spilled coolant and** (*b*) **start of coolant leakage after engine shutdown as a function of length of idle operation**

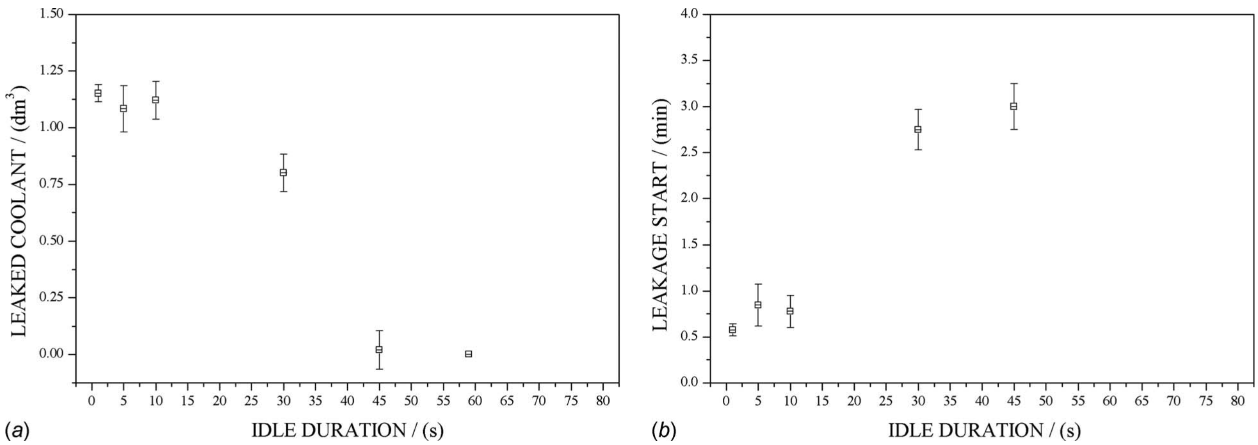


Fig. 9 (*a*) **Volume of the spilled coolant and** (*b*) **start of coolant leakage after engine shutdown as a function of length of idle operation. Cabin heater removed.**

4.4 Effect of Piping Length. To determine the effect of the engine-radiator piping length on the after-boiling phenomenon, new experiments were performed under the same test conditions of the baseline case described in Sec. 4.1.

Figure 13 shows the coolant pressure and temperature versus time for three different lengths of the engine-radiator connection, respectively, the baseline length of ≈85 cm (length of cooling circuit used in a production vehicle equipped with the same test engine, Figs. 13(*c*)), a reduced length of ≈40 cm (Fig. 13(*e*)), and an increased length of ≈190 cm (Fig. 13(*a*)).

Pressure evolution in the cooling circuit does not significantly differ during the initial stage of the phenomenon (phases *A* and *B*) for the three cases depicted in Fig. 13; some difference in the pressure level may be observed (compare Figs. 13(*a*), 13(*c*), and 13(*e*)), mainly owing to a much less repetitive behavior of the wax

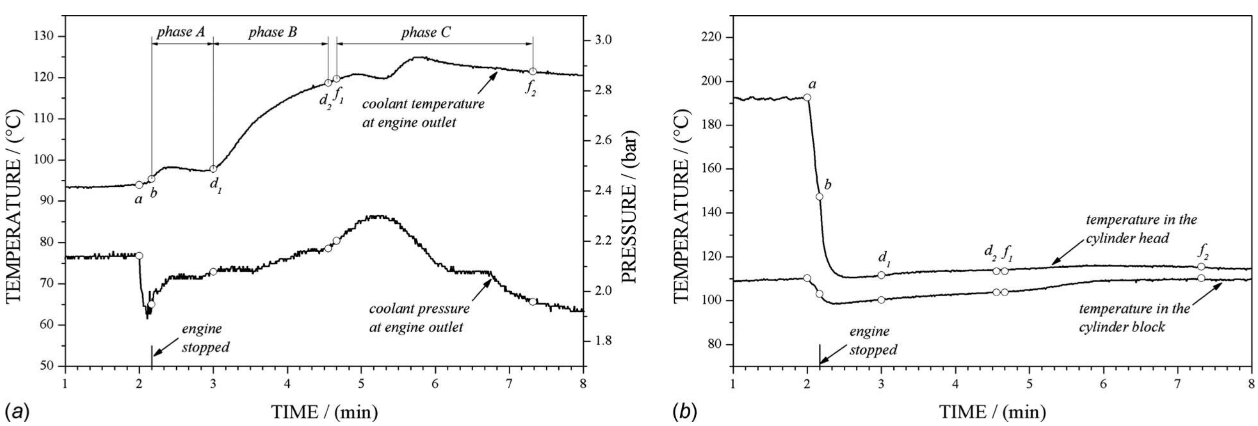


Fig. 10 (*a*) **Coolant and** (*b*) **metal conditions at two points in the cylinder head and cylinder block during the most rapidly varying part of the thermal evolution. Time of idle operation 5 s; initial load 819 kPa bmep; standard length of cooling circuit.**

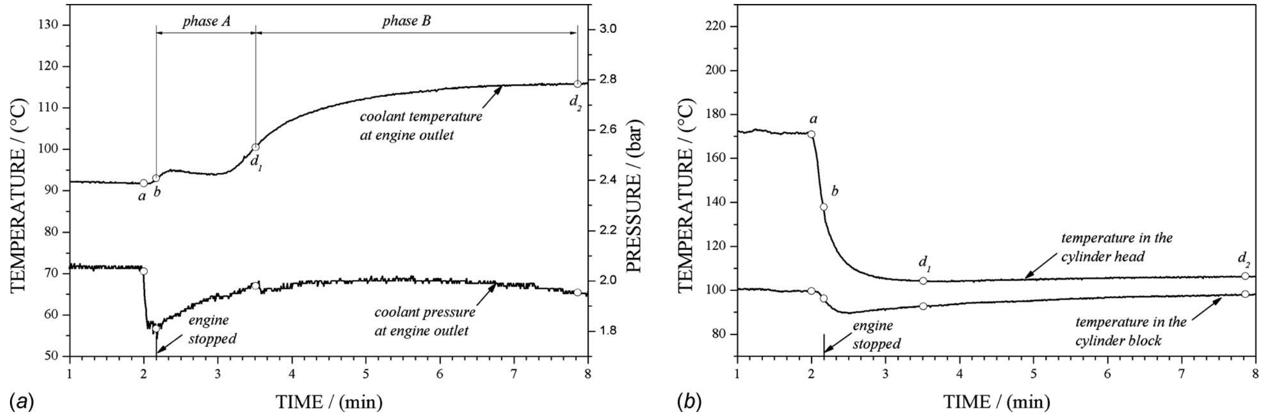


Fig. 11 (*a*) Coolant and (*b*) metal conditions at two points in the cylinder head and cylinder block during the most rapidly varying part of the thermal evolution. Time of idle operation 5 s; initial load 495 kPa bmep; standard length of cooling circuit.

three-way thermostat as consequence of the large number of tests under severe thermal-stress conditions. The main difference may be observed on the curves in Fig. 13 at the final stage (phase *C*). If the length of the engine-radiator piping is reduced, the vapor enters the radiator earlier (point f_v, Figs. 13(*c*) and 13(*e*)), where it condenses thus determining a rapid pressure drop. On the contrary, in the case of increased length of the engine-radiator piping of ≈190 cm (Fig. 13(*a*)), the vaporized mass of coolant does not reach the radiator, and the refrigerant cools in the form of stagnant vapor due to free convection heat losses.

The volume of spilled coolant versus the duration of coolant leakage and the vapor arrival time to the radiator after engine shutdown are reported in Fig. 14 for the three investigated engine-radiator piping lengths. The results show that by increasing the length of the engine-radiator connection the coolant leakage lasts longer. For the cases of reduced length (≈40 cm) and baseline length (≈85 cm), the end of leakage is determined by the vapor inlet time inside the radiator. On the contrary, by significantly increasing the engine-radiator piping length, the end of coolant leakage is due to free convection heat losses to the environment and by the loss of mass itself. Heat losses in this last case cause a reduction in the coolant mean temperature and, consequently, of the coolant saturation pressure. This determines the end of vapor production inside the cooling system and the beginning of vapor condensation inside the external cooling circuit, as visually observed through the stretches of transparent tubes.

5 Summary and Conclusions

The transient thermal evolution of a production small SI engine was investigated in the time interval, which follows the engine shutdown after a prolonged time of full or part load operation and at several times of idle operation.

The results show that the rapid shutdown of an engine causes a rapid coolant temperature increase, with the production of significant vapor quantities and pressure increments. The pressure rise often causes opening of the radiator pressure relief valve and loss of an important quantity of coolant.

The phenomenon is characterized by a considerable variability, and its evolution depends on the time of idle operation, on the initial engine load, and on the length of the engine-radiator connection.

The following conclusions can be drawn from the reported tests.

- The evolution of the coolant conditions (pressure and temperature) is very similar if the time of idle operation varies from 1 s to 10 s. In this case the coolant leakage starts 30–45 s after engine shutdown and the leaked refrigerant is ∼1 l.
- By extending the time of idle operation the increase of coolant temperature and pressure is more gradual, and also the metal temperature variation is less severe. However, even in

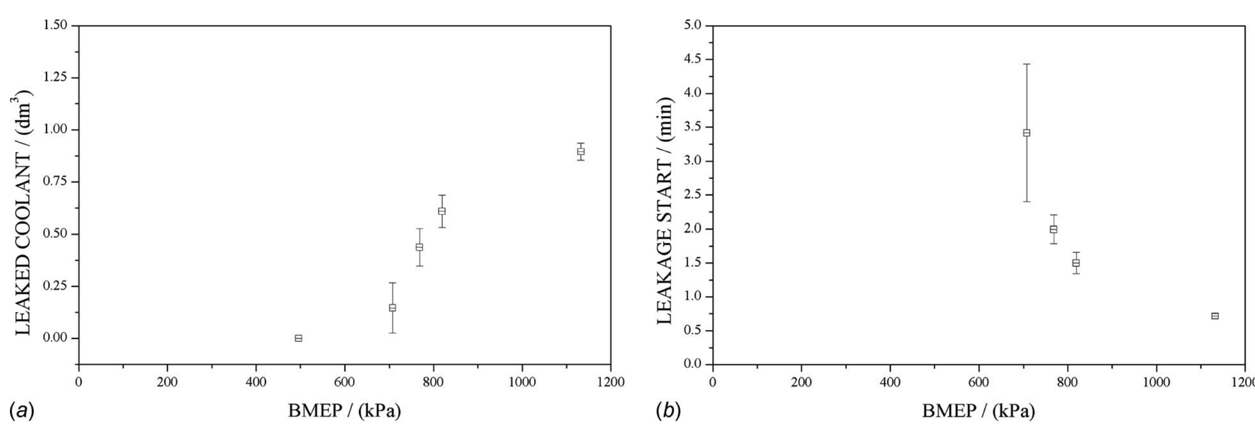


Fig. 12 (*a*) Volume of the spilled coolant and (*b*) start of coolant leakage after engine shutdown as a function of brake mean effective pressure

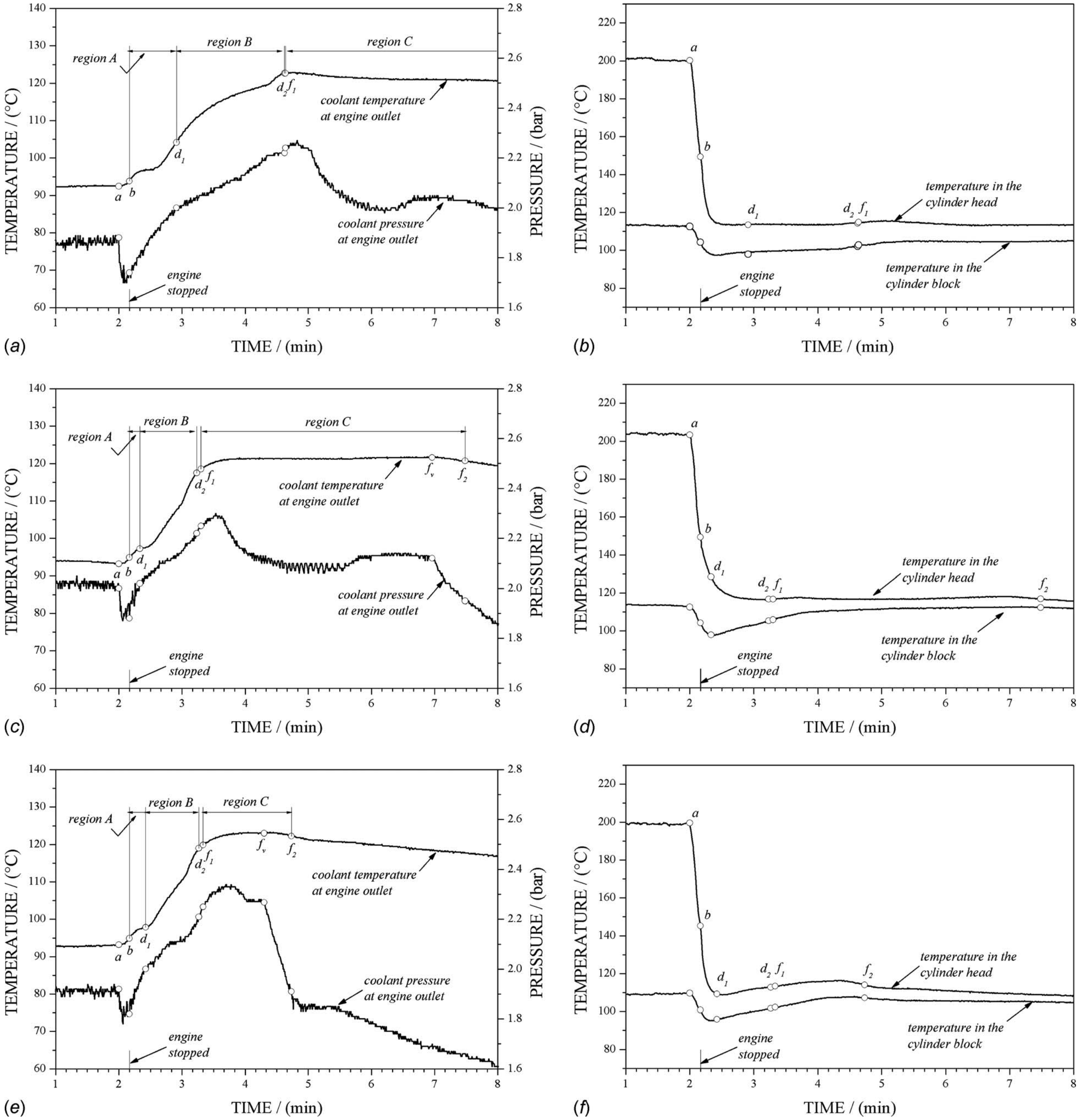


Fig. 13 Coolant and metal conditions at two points in the cylinder head and cylinder block during the most rapidly varying part of the thermal evolution. Time of idle operation 5 s, initial load at WOT. (*a*) and (*b*): increased length of cooling circuit of ≈190 cm; (*c*) and (*d*): baseline length of cooling circuit of ≈85 cm; (*e*) and (*f*): reduced length of cooling circuit of ≈40 cm.

the case of idle operation prolonged for 45 s, the quantity of spilled coolant may be significant (~0.43 l), and the start of leakage occurs about 2 min and 23 s after engine shutdown.

- The limit time of idle operation in order to avoid the coolant leakage is about 80 s for the WOT condition of the reported tests.
- Experiments were also repeated at part load, with the aim to investigate the behavior of the cooling system, with the engine initially operated at more typical driving conditions; the results show that also in this case the after-boiling phenomenon may occur, and the quantity of spilled coolant may still be significant (~0.6 l for the case of 819 kPa bmep). The introduction of a small electric pump, in addition to the main mechanical pump, can definitely represent an easy and efficient solution to the problem by permitting a cooling strategy also after engine shutdown.
- The limit load condition in order to avoid the coolant leakage corresponds to a 495 kPa bmep.
- The after-boiling phenomenon is less severe if the engine-to-radiator connection is shorter.
- In spite of the large number of tests under severe thermal-stress conditions, no damage was observed in the engine. Only the wax three-way thermostat and the radiator pressure relief valve showed a much less repetitive behavior and were substituted.

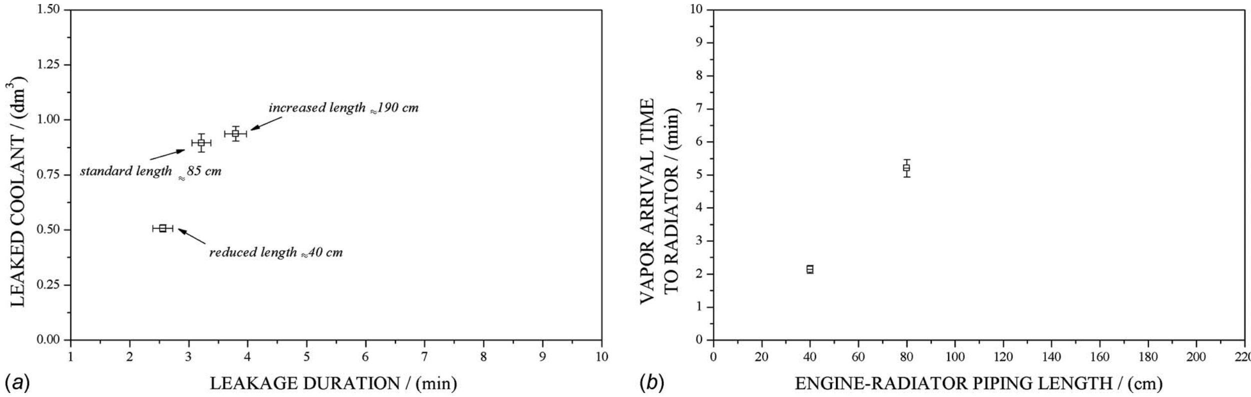


Fig. 14 (***a***) **Volume of the spilled coolant versus leakage and** (***b***) **vapor inlet time inside radiator after engine shutdown as a function of engine/radiator piping length**

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