An internal combustion engine has a variable speed coolant pump which is operated at a variable duty-cycle at lower coolant temperatures, while transitioning to a predetermined fixed speed during a final warmup period of operation, and finally to a select-speed operation at one of a selected number of steady state operating speeds selected as a function of at least engine load.
Figure 2
INTERNAL COMBUSTION ENGINE WITH VARIABLE SPEED COOLANT PUMP

CROSS REFERENCE TO RELATED APPLICATIONS

None.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to an internal combustion engine having a coolant pump with a drive speed which is controlled independently of the rotational speed of the engine.

2. Disclosure Information

Hybrid vehicles have been the subject of ever-increasing engineering activity prompted by the desire for increased vehicular fuel economy. One of the principle mechanisms employed with hybrid vehicles to greatly increase fuel economy is the stop-start mode of operation in which the vehicle’s engine is shut down when the vehicle is stopped in traffic, such as at a traffic signal. Of course, it is desirable to keep various vehicle systems in operation notwithstanding the vehicle’s engine has been shut down, and for this reason many accessories such as a power steering pump and an air conditioning compressor have been migrated from traditional mechanical drives to electro drives. In the case of a vehicle water pump, or coolant pump, there has been general recognition of benefits obtained from removing the coolant pump—often the last component powered by a front end accessory drive of an engine—from the engine and replacing the mechanical pump with an electric pump. Known electric pumps, however, are not generally well-suited for use with passenger automotive vehicles because such pumps operate in a manner which generally inhibits warmup of the engine, while overcooling the engine in certain operating modes, while at the same time consuming more power than is necessary to achieve the required cooling.

It would be desirable to provide a motor-driven coolant pump which promotes rapid, safe, and complete warmup of a vehicle engine, while minimizing energy consumption when a normal, stable, operating temperature has been reached, while at the same time providing heated coolant to a cabin heater in the event that the vehicle’s engine has been turned off.

SUMMARY OF THE INVENTION

According to an aspect of the present invention, an internal combustion engine includes an engine housing having a number of coolant passages and a heat exchanger for rejecting heat from coolant circulated from the engine housing. A variable speed coolant pump circulates coolant from the engine housing to the heat exchanger. The coolant pump operates according to a predetermined variable duty cycle at lower coolant temperatures. The pump operates at a selected one of a number of predetermined fixed speeds, as a function of at least engine speed and engine load, once the engine has attained a higher, stable operating temperature. Once a stable operating temperature has been reached, the pump’s operating speed may additionally be a function of engine coolant temperature. Operation of the pump at a variable duty cycle may be accomplished at either a fixed or a variable speed, but preferably occurs at a variable speed. According to another aspect of the present invention, the coolant pump is operated at a predetermined fixed speed if heat is requested by a passenger cabin heater furnished with coolant by the pump.

According to another aspect of the present invention, the pump is preferably driven by a motor, such as an electric motor or a fluid motor. Alternatively, the pump may be driven by a variable speed drive connected with the engine’s crankshaft or camshaft.

According to another aspect of the present invention, a method for operating a variable speed coolant pump for circulating liquid coolant through the housing of an internal combustion engine, as well as through a heat exchanger, includes duty-cycle operation of the pump initially at a variable duty-cycle selected as a function of at least a temperature of the engine, and select-speed operation of the pump at a selected one of several predetermined fixed speeds, with the speed being selected as a function of at least engine speed and engine load, once the engine has attained a higher, stable operating temperature.

The present method further includes operating the pump during final warmup at a single predetermined fixed speed between the period of duty-cycle operation and the period of select-speed operation.

According to another aspect of the present method, the duty-cycle operation includes a first period of operation at a shorter duty-cycle, while the coolant temperature is below a first temperature threshold, and a second period of operation, at a longer duty-cycle, while the coolant is between the first temperature threshold and a second, higher temperature threshold. Operation at the greater duty-cycle may be followed by operation of the pump at a single predetermined fixed speed during final warmup at temperatures between the second threshold and a third temperature threshold which is higher than the second threshold.

According to another aspect of the present invention, a hybrid vehicle includes an internal combustion engine and an energy storage device incorporated in a regenerative braking system. A cooling system for the engine includes an engine housing having a number of coolant passages, a heat exchanger for rejecting heat from coolant circulated from the engine housing, and a variable speed coolant pump for circulating coolant from the engine housing to the heat exchanger, with the coolant pump operating according to a predetermined variable duty-cycle at lower coolant temperatures, and with the pump operating at a selected one of a number of predetermined fixed speeds, as a function of at least engine speed and engine load, once the engine has attained a stable operating temperature.

It is an advantage of a system and method according to the present invention that an internal combustion engine may be warmed rapidly, so as to help minimize exhaust emissions and fuel consumption, particularly by allowing a hybrid vehicle to transition rapidly into a stop-start mode of operation.

It is another advantage of a method and system according to the present invention that an engine equipped with the system may be operated economically once it has reached a stable operating temperature, because the coolant pump will extract no more work than is necessary for the real-time operating conditions of the engine.
Other advantages, as well as features of the present invention will become apparent to the reader of this specification.

**BRIEF DESCRIPTION OF THE DRAWINGS**

[0017] FIG. 1 is a schematic representation of a hybrid vehicle having a cooling system according to the present invention.

[0018] FIG. 2 is a plot showing operation of a variable speed coolant pump according to an aspect of the present invention.

**DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS**

[0019] As shown in FIG. 1, internal combustion engine 18 has an engine housing 42, with a number of coolant passages 44. A heat exchanger 46, rejects heat from coolant circulated from engine housing 42. A variable speed coolant pump 34, circulates coolant from engine housing 42 to heat exchanger 46. Coolant pump 34 is driven by a motor 38 which may be configured as either an electric motor, or a fluid motor, or a mechanical or fluid drive associated with a crankshaft or camshaft (neither is shown) of engine 18.

[0020] Pump 34 and motor 38 are controlled by controller 50, which is operatively connected with not only motor 38 and pump 34, but also with engine 18, and energy storage device 30.

[0021] Energy storage device 30 may be configured as either an electrical traction battery, or a pumped storage device such as a hydraulic or compressed gas energy storage device. Energy storage device 30 is connected with pump motor 22, which may be configured as either a fluid pump and motor, or as an electrical generator and motor. Pump motor 22 either alone, or in combination with engine 18, powers final drive 26, which in turn powers a pair of road wheels 14. When operated in a regenerative braking mode, final drive 26 rotates pump/motor 22 so as to provide energy to storage device 30. Depending upon whether vehicle 10 is a so-called hard or soft hybrid, engine 18 may be rotated in unison with generator/motor 22 or not. This detail is beyond the scope of the present invention.

[0022] The main purpose of pump 34 is to circulate coolant from engine 18 through heat exchanger 46 and, if called for, to cabin heater 40, which has access to coolant controlled by means of valves 41. Controller 50 operates pump 34 and motor 38 according to the scheme shown generally in FIG. 2. Thus, when engine 18 is started cold, controller 50 will operate motor 38 initially at a variable duty-cycle selected as a function of at least a temperature of engine 18. In a preferred embodiment, the temperature of a cylinder head of engine 18 is used as a control parameter. The first period of operation, shown as duty-cycle A of FIG. 2, is a shorter duty-cycle employed when the coolant temperature is below a first threshold shown at temperature T1. This shorter duty-cycle, A, is used to circulate coolant minimally through passages 44, so as to avoid any significant cooling of the engine, while preventing hot spots at locations adjacent the combustion chambers of engine 18. Once temperature T1 has been reached, controller 50 operates pump 34 and motor 38 according to duty-cycle B, which is a longer duty-cycle characterized by purposeful circulation of coolant within coolant passage 44 located within engine housing 42. In essence, during operation of duty-cycle B between temperatures T1 and T2, the engine coolant is warmed uniformly.

[0023] Once engine operating temperature exceeds temperature T2, the final warmup stage is entered. Thus, between temperatures T2 and T3 of FIG. 2, pump 34 is operated at a single, predetermined, fixed speed which allows final warm-up, without overcooling engine 18. The prevention of overcooling is important because stop-start operation desirably occurs only when temperature T3 has been attained, and it is desirable to obtain this level of control as soon as possible during each operating episode of engine 18, so as to allow engine 18 to be shut off if vehicle 10 is stopped, for example, at a traffic signal.

[0024] Once temperature T3 has been attained, controller 50 will operate pump 34 in select-speed operation mode. While in select-speed operation, pump 34 is operated at a selected one of a number of predetermined fixed speeds as a function of at least the rotational speed of engine 18, and the load imposed on engine 18 by the vehicle driver and by pump/motor 22. An operating temperature of engine 18, such as cylinder head temperature may also be employed in the selection of the pump speed at temperatures in excess of T3. In any event, a purpose of the cooling system is to maintain the temperature at a value less than $t_{max}$.

[0025] According to another aspect of the present invention, a method for operating variable speed coolant pump 34 includes duty-cycle operation, such as at duty-cycles A and B, of FIG. 2, initially, or in other words, at cold startup, with duty-cycles A and B being selected as a function of at least a temperature of engine 18, followed by select-speed operation of pump 34, with pump speed being selected as a function of at least the rotational speed of engine 18 and load imposed upon engine 18, provided engine 18 has attained a stable operating temperature. In one example, pump 38 was operated at a duty-cycle A of about 20%, from a cold start-up of approximately 70° F. until a cylinder head temperature of about 180° F. (T1) was reached. Then, operation continued at a duty-cycle B of about 50% until a cylinder head temperature of about 188° F. (T2) was attained. This was followed by a period of final warmup operation at a fixed speed of about 1300 RPM until a temperature of about 190° F. (T3) was realized. Then, select speed operation ensued at pump speeds ranging from about twice engine speed at idle to pump speeds approximating engine speed at high loads and the highest engine speeds. While operating in the select speed mode, the pump speed will be chosen as a function of the engine’s operating condition, including at least engine load, as determined by engine and vehicle operating parameters such as throttle position.

[0026] Controller 50 has the capability to further control engine 18 by shutting engine 18 off for brief periods once temperature T3 has been attained and vehicle 10 has been brought to an idle condition, such as at a traffic signal. In the event that cabin heater 40 is in a demand mode, valves 41 and pump 34 may be operated by controller 50 so as to circulate engine coolant through heater 40 without causing the coolant to be circulated through heat exchanger 46. In this manner, the passenger cabin of vehicle 10 may be provided with heat even when engine 18 is not running, without rejecting heat to the atmosphere. Alternatively, heat exchanger 46 may be included in the coolant flow path, so as to provide additional cooling capacity for engine 44.

[0027] Although the present invention has been described in connection with particular embodiments thereof, it is to be
understood that various modifications, alterations, and adaptations may be made by those skilled in the art without departing from the spirit and scope of the invention set forth in the following claims.

What is claimed is:

1. An internal combustion engine, comprising:
   an engine housing having a plurality of coolant passages;
   a heat exchanger for rejecting heat from coolant circulated from said engine housing; and
   a variable speed coolant pump for circulating coolant from said engine housing to said heat exchanger, with said coolant pump operating according to a predetermined, variable duty cycle at lower coolant temperatures, and with the pump operating at a selected one of a plurality of predetermined fixed speeds, as a function of at least engine speed and engine load, once the engine has attained a higher, stable operating temperature.

2. An internal combustion engine according to claim 1, wherein the operating speed of said pump is additionally a function of engine coolant temperature.

3. An internal combustion engine according to claim 1, wherein said pump is operated at a predetermined fixed speed if heat is requested from a passenger cabin heater furnished with coolant by said pump.

4. An internal combustion engine according to claim 1, wherein said pump is driven by a motor.

5. An internal combustion engine according to claim 4, wherein said pump is driven by an electric motor.

6. An internal combustion engine according to claim 4, wherein said pump is driven by a fluid motor.

7. An internal combustion engine according to claim 1, wherein said pump is shut off when the engine is turned off, unless heat is requested from a passenger cabin heater furnished with coolant by said pump.

8. An internal combustion engine according to claim 1, wherein operation of said pump at said variable duty cycle is at a fixed speed.

9. An internal combustion engine according to claim 1, further comprising a controller for operating said pump.

10. A method for operating a variable speed coolant pump for circulating liquid coolant through a housing of an internal combustion engine, as well as through a heat exchanger, comprising:
    duty cycle operation of the pump initially at a variable duty cycle selected as a function of at least a temperature of the engine; and
    select-speed operation of the pump at a selected one of a plurality of predetermined fixed speeds, with said speed being selected as a function of at least engine speed and engine load, once the engine has attained a stable operating temperature.

11. A method according to claim 10, further comprising operating the pump during final warmup at a single predetermined fixed speed between said duty cycle operation and said select-speed operation.

12. A method according to claim 10, wherein said duty cycle operation comprises a first period of operation at a shorter duty cycle, while the coolant temperature is below a first threshold, and a second period of operation, at a longer duty cycle, while the coolant is between said first threshold and a second, higher threshold.

13. A method according to claim 12, wherein operation at said longer duty cycle is followed by operation of the pump during a third time period at a single predetermined fixed speed during final warmup at temperatures between said second threshold and a third threshold which is higher than the second threshold.

14. A method according to claim 13, wherein said select-speed operation is initiated at coolant temperatures above said third threshold.

15. A method according to claim 10, wherein said duty cycle operation comprises a first period of operation at a shorter duty cycle in the range of 10%-20%, while the coolant temperature is below a first threshold, and a second period of operation, at a longer duty cycle, in the range of 40%-60%, while the coolant is between said first threshold and a second, higher threshold.

16. A method according to claim 10, wherein said duty cycle operation comprises a first period of operation at a shorter duty cycle, while the coolant temperature is below a first threshold, and a second period of operation, at a longer duty cycle, while the coolant is between said first threshold and a second, higher threshold, with said duty cycle operation occurring at a fixed pump speed.

17. A hybrid vehicle, comprising:
   an internal combustion engine;
   an energy storage device incorporated in a regenerative braking system; and
   a cooling system for said engine, with said cooling system comprising:
   an engine housing having a plurality of coolant passages;
   a heat exchanger for rejecting heat from coolant circulated from said engine housing; and
   a variable speed coolant pump for circulating coolant from said engine housing to said heat exchanger, with said coolant pump operating according to a predetermined, variable duty cycle at lower coolant temperatures, and with the pump operating at a selected one of a plurality of predetermined fixed speeds, as a function of at least engine speed and engine load, once the engine has attained a stable operating temperature.

18. A hybrid vehicle according to claim 17, wherein said pump is operated at a predetermined fixed speed if heat is requested from a passenger cabin heater furnished with coolant by said pump.

19. A hybrid vehicle according to claim 17, further comprising a controller, connected with said engine and said energy storage device, for operating said pump, as a function of engine speed, engine temperature, and engine load.

20. A hybrid vehicle according to claim 17, further comprising a controller, connected with said engine and said energy storage device, for operating said pump, as a function of engine speed, engine temperature, and engine operating condition.

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