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Collins, Colorado 80525 (US). **MOLENAAR, Gregory A.** [US/US]; 1700 Concord Drive, Fort Collins, US 80526 (US).

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(74) Agent: **MAKEEVER, Jeffery J.**; Reinhart Boerner Van Dueren P.C., 2215 Perrygreen Way, Rockford, Illinois 61107 (US).

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(71) Applicant (for all designated States except US): **WOODWARD GOVERNOR COMPANY** [US/US]; 1000 E. Drake Road, P.O. Box 1519, Fort Collins, Colorado 80525 (US).

(72) Inventors; and

(75) Inventors/Applicants (for US only): **PATERSON, Clark** [US/US]; 2980 Westminster Court, Loveland, Colorado 80538 (US). **VAN DYNE, Ed** [US/US]; 2604 Farisita Drive, Loveland, Colorado 80538 (US). **WOOLSTON, Mark R.** [US/US]; 408 Strasburg Drive A-2, Fort

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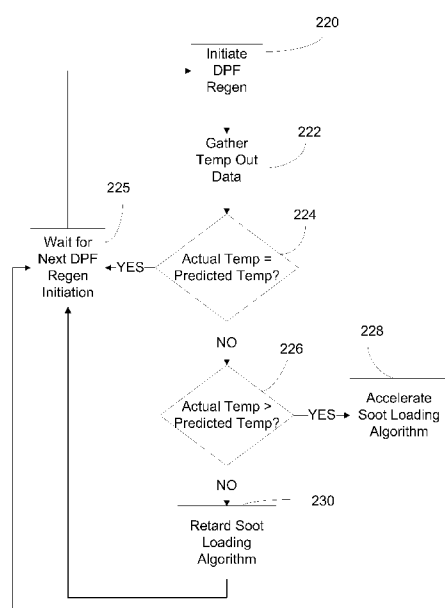


FIG. 5

(57) Abstract: Systems and methods to determine conditions of a diesel particulate filter (DPF) based on correlation between predicted and actual thermal data of the fluid exiting a DPF are provided. Soot loading, ash loading, and/or DPF damage may be detected, and DPF operational models may be calibrated in accordance with such systems and methods. Further, initiation of regeneration may also be effected in accordance with such systems and methods.



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SYSTEM AND METHOD FOR DETECTING DIESEL PARTICULATE FILTER CONDITIONS BASED ON THERMAL RESPONSE THEREOF

FIELD OF THE INVENTION

[0001] This invention generally relates to diesel particulate filter (DPF) systems and more specifically to a system and method for determining soot and ash accumulation in a DPF.

BACKGROUND OF THE INVENTION

[0002] Increasing environmental restrictions and regulations are causing diesel engine manufacturers and packagers to develop technologies that improve and reduce the impact that operation of such engines have on the environment. As a result, much design work has gone into the controls that operate the combustion process within the engine itself in an attempt to increase fuel economy and reduce emissions such as NO_x and particulates. However, given the operating variables and parameters over which a diesel engine operates and given the tradeoff between NO_x and particulate generation, many engine manufacturers and packagers have found it useful or necessary to apply exhaust after-treatment devices to their systems. These devices are used to filter the exhaust gas flow from the diesel engine to remove or reduce to acceptable levels certain emissions. Such devices are particularly useful in removing exhaust particulates, or soot, from the exhaust gas flow before such soot is released into the environment.

[0003] One such exhaust after-treatment device is called a Diesel Particulate Filter (DPF). The DPF is positioned in the exhaust system such that all exhaust gases from the diesel engine flow through it. The DPF is configured so that the soot particles in the exhaust gas are deposited in the filter substrate of the DPF. In this way, the soot particulates are filtered out of the exhaust gas so that the engine or engine system can meet or exceed the environmental regulations that apply thereto.

[0004] While such devices provide a significant environmental benefit, as with any filter, problems may occur as the DPF continues to accumulate these particulates. After a period of time the DPF becomes sufficiently loaded with soot that the exhaust gases experience a significant pressure drop passing through the increasingly restrictive filter. As a result of operating with an overly restrictive filter, the engine thermal efficiency declines

because the engine must work harder and harder simply to pump the exhaust gases through the loaded DPF. Besides the reduced thermal efficiency, a second and potentially more dangerous problem may occur. Because the soot accumulated in the DPF is flammable, continued operation with a loaded DPF raises the serious potential for uncontrolled exhaust fires if and when the accumulated soot is eventually ignited and burns uncontrollably.

[0005] To avoid either occurrence the engine packager typically incorporates one of several possible filter heating devices upstream of the DPF to periodically clean the filter. These filter heating devices are used periodically to artificially raise the temperature of the exhaust stream to a point at which the accumulated soot will self-ignite. When initiated at a time before loading of the DPF becomes excessive, the ignition and burn off will occur in a safe and controlled fashion. This process of burning the soot in such a controlled manner is called regeneration. The control of the method to generate the supplemental heat necessary to increase the temperature in the DPF is critical to the safe and reliable regeneration. Typically the acceptable regeneration range is from 500 to 700 °C. Temperatures below this range are insufficient to ignite the accumulated soot, and temperatures above this range may cause thermal damage to the filter media.

[0006] Many methods have been devised to provide the auxiliary heat necessary to initiate regeneration. For example, the operating parameters of the diesel engine may be modified in such a manner to cause the exhaust temperature to rise to a level sufficient for proper operation of the downstream particulate filter. It is also possible to inject hydrocarbon fuel into the exhaust of a diesel engine immediately before the exhaust passes through a Diesel Oxidation Catalyst (DOC) positioned upstream of the particulate filter. The DOC converts the excess hydrocarbon fuel into heat by means of the catalytic reaction of the catalyst, thus increasing the exhaust gas temperature prior to its passage through the particulate filter. Supplemental heat may also be generated in the exhaust flow by use of an auxiliary electrical heater placed within the exhaust path. This supplemental heat is added to the exhaust gas prior to its passage through the particulate filter. As an alternative to the use of an electric heater, another method of filter regeneration uses a fuel-fired burner to heat the exhaust gas prior to the DPF.

[0007] The rate at which soot accumulates in the filter depends upon the operating regime of the engine. As such, besides the selection of the particular method or device to be used to heat the exhaust gas to enable regeneration, the engine manufacturer or packager must also determine when to initiate the regeneration process. If regeneration is initiated too soon when the DPF is only lightly loaded, the process will be inefficient. If the

regeneration is not initiated until the DPF is heavily loaded, the overall engine efficiency would have been unduly reduced as discussed above and there is a risk that the soot may self-ignite and/or that the burn may be unsafe and uncontrolled.

[0008] In an attempt to properly determine when to initiate the regeneration process, several sensors and control algorithms have been developed. These sensors and control algorithms are used to estimate the soot loading of the DPF so that regeneration can be initiated only after soot loading could cause an engine efficiency reduction but before excessive loading occurs actually resulting in such an efficiency reduction and raising the potential for self-ignition. Such methods range from simply monitoring the pressure differential across the DPF substrate to sophisticated models related to engine soot production rates and soot oxidation rates in the DPF. Unfortunately, the inherent inaccuracies of these methods necessitate high levels of redundancy in order to operate reliably.

[0009] There is a need in the art, therefore, to provide a system and method that allow a controller to gain information about the conditions of the DPF in order to increase the accuracy and/or robustness of the control algorithms pertaining to regeneration and maintenance of the DPF. Embodiments of the present invention provide such systems and methods.

BRIEF SUMMARY OF THE INVENTION

[0010] In view of the above, embodiments of the present invention provide new and improved systems and methods for determining conditions of the DPF to more effectively initiate a regeneration process to burn off the accumulated soot in the DPF in a safe and controlled manner, and to effectuate same. Other embodiments of the present invention provide new and improved systems and methods for determining conditions of the DPF to determine when soot and/or ash accumulation has reached a level that requires a change in the calibration, maintenance of the DPF, and/or ash removal. Still other embodiments of the present invention provide new and improved systems and methods for determining conditions of the DPF to determine if damage to the DPF has occurred requiring maintenance and repair thereof. Yet further embodiments of the present invention provide systems and methods that perform two or more of these functions.

[0011] One method according to an embodiment of the present invention is a method of detecting conditions of a diesel particulate filter (DPF) used in the exhaust system of a

diesel engine. The exhaust system including a heat addition device for initiating a regeneration of the DPF. The heat addition device could be the engine itself configured to perform a modified engine operation to generate the heat or an auxiliary heat device within the exhaust system and independent of the engine and downstream thereof. The heat addition device is controlled by a controller programmed with a regeneration algorithm that determines when to initiate the regeneration process. At least one sensor is coupled to the controller for monitoring input characteristics of exhaust entering the DPF including at least one temperature sensor for monitoring an input temperature of the exhaust entering the DPF. At least one sensor monitors an output temperature of the exhaust exiting the DPF. The method comprises several steps. A first step includes determining estimated thermal exit temperature data of the exhaust exiting the DPF based at least in part on the input characteristics of the exhaust entering the DPF. The method further includes measuring the output temperature of the exhaust exiting the DPF to determine actual thermal exit temperature data of exhaust exiting the DPF. Also, the method includes comparing the estimated thermal exit temperature data to the actual thermal exit temperature data to determine a difference therebetween. Finally the method includes determining a condition of the DPF by analyzing the difference therebetween.

[0012] In a more particular implementation of an embodiment of the invention, the method can be used to adjust when to initiate a subsequent regeneration based on the analyzed data. More particularly, the method includes initiating a regeneration of the DPF to remove soot from the DPF. The step of analyzing comprises the steps of integrating the difference between the estimated thermal exit temperature data and the actual thermal exit temperature data to determine an measured amount of soot burned during regeneration. Further, when this measured amount varies from a predetermined theoretical amount that should have been burned based on the predetermined amount of soot that should have been loaded in the DPF to initiate regeneration thereof, the method includes adjusting an initiation of a subsequent regeneration based on the amount of soot burned during the regeneration relative to a predicted amount of soot burned during the regeneration.

[0013] In a more particular implementation, the step of adjusting comprises the step of lengthening a period until initiation of the subsequent regeneration when the amount of soot burned is less than a predetermined amount and the step of adjusting comprises the step of shortening a period until initiation of the subsequent regeneration when the amount of soot burned is greater than a predetermined amount.

[0014] In an even more particular implementation, wherein the controller is programmed with a soot loading algorithm configured to determine when to initiate regeneration of the DPF by predicting soot loading of the DPF, the step of adjusting comprises adjusting the soot loading algorithm to reduce the time period until the next regeneration initiation when the amount of soot burned is greater than a predetermined amount and comprises adjusting the soot loading algorithm to increase the time period until the next regeneration initiation when the amount of soot burned is less than a predetermined amount. It should be noted that adjusting the time period until the next regeneration may not actually be an adjustment in actual time. But adjusting the time period could be accelerating or decelerating the calculations that determine how much soot loading has occurred, which may actually be time independent and wholly dependent on other factors such as exhaust flow rate, temperature, pressure, etc. However, the use of adjusting a time period shall be considered to include these adjustments.

[0015] In a further embodiment of the invention, the a form of the method can be used to recalibrate a thermal model of the DPF as a result of changes in thermal properties of the DPF from prolonged use, such as changes in the physical structure, increased ash and soot loading, etc. The method includes initiating an enhanced regeneration of the DPF to establish a baseline clean condition of the DPF. This method will typically be implemented after the DPF has been in operation for an extended period of time and typically after several DPF regenerations have occurred. Thus, the enhanced regeneration will remove, if possible, any excess soot that was not removed during prior standard DPF regenerations. After completion of the enhanced regeneration, a heat pulse is applied to the DPF for a predetermined length of time. After initiation of the heat pulse, the method includes determining the estimated thermal exit temperature data of the exhaust exiting the DPF based at least in part on the input temperature of the exhaust entering the DPF during the heat pulse. Further, the method includes measuring the output temperature of the exhaust exiting the DPF during the heat pulse to determine actual thermal exit temperature data of the exhaust exiting the DPF during the heat pulse. The estimated thermal exit temperature data during the heat pulse is then compared to the actual thermal exit temperature data of the heat pulse to determine a calibration difference therebetween. Finally, the method includes calibrating the step of determining an estimated thermal exit temperature data of exhaust exiting the DPF during a subsequent process based on the calibration difference. In a particular implementation, this calibration step includes calibrating the thermal model of the DPF used during the step of determining the estimated thermal exit temperature data of the exhaust exiting the DPF based on the calibration difference.

[0016] In a further more particular implementation, the step of analyzing the difference to determine the condition of the DPF comprises the step of providing an indication that maintenance of the DPF is required when the difference indicates that the actual thermal exit temperature data is less than or different than the estimated thermal exit temperature data by a predetermined amount. Typically, when the DPF becomes too loaded with ash as a result of numerous regeneration process, the loaded ash will affect the thermal properties of the DPF thereby effecting the exit temperature of the exhaust. When this exit temperature of the exhaust varies too significantly from a predetermined or the predicted value, then the system will determine and indicate that maintenance needs to occur as the DPF regeneration is not sufficient to clean the DPF.

[0017] In a further method, the step of analyzing the difference to determine the condition of the DPF comprises the step of providing an indication that damage to the DPF has occurred. This may happen when the difference between the predicted and the measured temperature data indicates that at least a portion of the actual thermal exit temperature data has a rate of change that is different than a rate of change of a corresponding portion of the estimated thermal exit temperature data by a predetermined amount. By analyzing different characteristics of the thermal data, different information can be determined. For instance, the rate of change can indicate that there is damage because, for example, the flow rate of the exhaust through the DPF may be retarded or accelerated adjusting how quickly the exit temperature will increase, thus indicating the condition of the DPF.

[0018] The method may use a heat pulse step for various reasons. In one implementation, the system and method may be used to initially calibrate the DPF system prior to use, such as during a new hardware self-calibration. As such, a heat pulse may be sent through the DPF before any soot loading has occurred and prior to any DPF regenerations so as to run an initial calibration on the system. The method of analyzing the predicted and actual temperature data will then be used to calibrate the predicted temperature data. In this application, because there has been no soot loading of the DPF, the measured temperature data can adjust for variations in the DPF from the actual thermal model or due to lower quality instrumentation, etc.

[0019] Alternatively, a thermal pulse may be sent and the actual and predicted values may be compared/analyzed to determine the soot loading of the DPF. When a variation between the two values occurs, the variation may be attributable to soot loading of the DPF which will alter the thermal characteristics of the DPF. In such an embodiment, if the

difference is outside a predetermined range, the data may be used to then initiate a regeneration.

[0020] An apparatus according to the present invention includes a diesel particulate filter (DPF) system for removing particulates from diesel engine exhaust. The DPF system includes a DPF, a heat addition device which may be an auxiliary component or the engine configured to perform a heat generation operation. The system also includes DPF input and output temperature sensors positioned to sense temperature of fluid entering and exiting the DPF. A controller is configured to control the heat addition device to initiate regeneration of the DPF based on a regeneration algorithm. The controller is configured to determine estimated thermal data of the DPF based at least in part on the input temperature of the fluid (e.g. exhaust) entering the DPF, to measure the output temperature of the fluid exiting the DPF to determine or gather actual thermal data of the fluid exiting DPF, to compare the estimated thermal data to the actual thermal data to determine a difference therebetween, and to analyze the difference to determine the condition of the DPF.

[0021] In a more preferred implementation, the controller is configured to integrate the difference between the actual and predicted temperature data to determine an amount of soot burned during regeneration. The controller is also configured to adjust when a subsequent regeneration is initiated based on the amount. More particularly, in one embodiment, the controller is configured to lengthen a period until a subsequent regeneration when the amount of soot burned is less than a predetermined amount and wherein the controller is configured to shorten a period until the subsequent regeneration when the amount of soot burned is greater than a predetermined amount. Again shortening and lengthening the period until subsequent regenerations may not be actual time adjustments but may be accelerating or decelerating the determination of soot loading so as to more properly determine when to initiate a subsequent regeneration.

[0022] In a further implementation of the system, the controller is further configured to initiate an enhanced regeneration of the DPF to establish a baseline clean condition of the DPF, such as after a plurality of regeneration processes have occurred. After completion of the enhanced regeneration, the controller is configured to apply a heat pulse to the DPF, to determine the estimated thermal data of the fluid exiting the DPF as a result of the heat pulse, to measure the output temperature of the fluid exiting the DPF as a result of the heat pulse to determine the actual thermal data of fluid exiting the DPF, to compare the estimated thermal data to the actual thermal data to determine a calibration difference therebetween, and to calibrate the controller's configuration to determine the estimated

thermal data of the fluid exiting the DPF during a subsequent process based on the calibration difference.

[0023] The controller may also be configured to provide an indication that maintenance of the DPF is required when the difference indicates that the actual thermal data is less than the estimated thermal data by a predetermined amount. Similarly, the controller may also or individually be configured to provide an indication that the DPF is damaged when the difference between the actual and predicted temperature data indicates that at least a portion of the actual thermal exit temperature data has a rate of change that is different than a rate of change of a corresponding portion of the estimated thermal exit temperature data by a predetermined amount.

[0024] Further yet, in one embodiment the controller is configured to apply a heat pulse to the DPF prior to determining the estimated thermal data of the DPF, to determine the estimated thermal data of the DPF based at least in part on the input temperature of the DPF during the heat pulse, to measure the output temperature of the DPF during the heat pulse determine actual thermal data of the DPF during the heat pulse, to compare the estimated thermal data during the heat pulse to the actual thermal data during the heat pulse to determine a calibration difference therebetween, and to calibrate its configuration to determine the estimated thermal data of the DPF based at least in part on the input temperature of the DPF during the subsequent regeneration based on the calibration difference. This heat pulse analysis may occur as a new hardware self-calibration prior to any soot loading.

[0025] A further method according to the present invention includes detecting conditions of a diesel particulate filter. The method includes the steps of initiating a heat pulse; determining estimated thermal data of fluid exiting the DPF based on the heat pulse; measuring the output temperature of the fluid exiting the DPF to determine actual thermal data of the fluid exiting the DPF as a result of the heat pulse; comparing the estimated thermal data to the actual thermal data to determine a difference therebetween; and calibrating a thermal model of the DPF based on the difference. In one implementation, all steps are performed for at least a first time as a new system calibration. In a different implementation, the method further includes the step of initiating an enhanced regeneration to establish a clean baseline of the DPF and wherein all steps are performed after the step of initiating the enhanced regeneration, and the step of calibrating updates the thermal model to compensate for changes in the DPF due to particulate (e.g. ash or soot that cannot be removed by regeneration or enhanced regeneration) loading of the DPF.

[0026] Other aspects, objectives and advantages of the invention will become more apparent from the following detailed description when taken in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0027] The accompanying drawings incorporated in and forming a part of the specification illustrate several aspects of the present invention and, together with the description, serve to explain the principles of the invention. In the drawings:

[0028] FIG. 1 is a simplified system level diagram of a DPF soot loading determination and regeneration system constructed in accordance with one embodiment of the present invention;

[0029] FIG. 2 is a graphical illustration of DPF thermal data/profiles for input temperature, predicted output temperature and actual output temperature measured during a regeneration event;

[0030] FIG. 3 is a graphical illustration of DPF thermal data/profiles for input temperature, predicted output temperature and actual output temperature measured during a test pulse event;

[0031] FIG. 4 is a graphical illustration of DPF thermal data/profiles for input temperature, predicted output temperature and actual output temperature measured during a self-test event illustrating damage to the DPF; and

[0032] FIGS. 5-8 are flow charts illustrating various methods for analyzing the conditions of a DPF and updating control systems of a regeneration system based on the condition of the DPF.

[0033] While the invention will be described in connection with certain preferred embodiments, there is no intent to limit it to those embodiments. On the contrary, the intent is to cover all alternatives, modifications and equivalents as included within the spirit and scope of the invention as defined by the appended claims.

DETAILED DESCRIPTION OF THE INVENTION

[0034] Turning now to the drawings, there is illustrated in FIG. 1 an embodiment of a system 100 that is configured to determine an appropriate time to initiate regeneration of a diesel particulate filter (DPF) 102 with which embodiments of the system and method of the present invention find particular applicability. It should be noted, however, that while embodiments of the system and method of the present invention find applicability to such a system, its applicability is not so limited. That is, embodiments of the system and method of the present invention may find applicability to other systems and algorithms that determine when to initiate the regeneration process, and such use is reserved herein. Further, these systems may include more or less components than illustrated in FIG. 1.

[0035] Regardless of the algorithm utilized to determine when to initiate the regeneration process, embodiments of the present invention provide the capability of determining various conditions of the DPF 102. Such information may be used to determine when to initiate regeneration of the DPF 102, to adjust the algorithm that determines the appropriate time to initiate regeneration of the DPF 102, to re-calibrate the algorithm, and/or to determine whether ash accumulation within the DPF 102 has reached a point where maintenance and ash removal is required. This information may also or alternatively be used to determine if damage to the DPF 102 itself has occurred and will require repair. Indeed, embodiments of the present invention may utilize the information for one or more of these purposes, and as such it should be appreciated that no single embodiment need perform all such available functions since each provides distinct advantages. The individual features will be generally discussed independently, but it should be noted that these features and methods can be combined into more complex systems that perform one or more methods simultaneously or sequentially. Such variations are contemplated embodiments of the present invention.

[0036] As discussed briefly above and returning specifically to FIG. 1, the DPF 102 is installed in an engine exhaust stream to filter out particulates from the diesel engine 106 exhaust. In order to clean the collected particulates, e.g. soot, off of the DPF 102, a heat addition device 104 may be used upstream of the DPF 102 but downstream from the engine 106. Such a heat addition device 104 may be any source of auxiliary heat, such as a fuel fired burner, an electrical heater, RF heater, DOC, or in the absence of a device, via modified engine operation. As used herein, a modified engine operation shall be considered a heat addition device unless explicitly distinguished. But embodiments are clearly contemplated where the engine or a modified engine operation are not the heat addition

device, but that the heat addition device is provided by a separate component downstream from the engine. The system controller 108 in one embodiment also receives exhaust temperature input from sensors 110, 112 positioned to sense the temperature of the exhaust gas at different locations throughout the system 100.

[0037] In one embodiment of the system and method of the present invention, temperature sensors 110 and 112 are utilized. This system compares a thermal prediction or estimate of the DPF 102 output temperature (DPF 102 output temperature shall in one embodiment, at least, be the temperature of the exhaust gas as it exits the DPF 102) generated from a thermal model of the DPF 102 to a measured value from sensor 112 in order to determine information about the DPF 102 conditions and state. In embodiments of the present invention, a thermal model is created for the DPF 102. The thermal model includes parameters about the DPF 102 and its thermal properties as well as other parameters relating to the thermal response of the DPF 102. Based on the thermal properties and parameters of the DPF 102, the thermal model can be derived using standard thermodynamic concepts and principles. Flow conditions of the exhaust gas passing into/through the DPF 102 are then monitored or predicted from inputs based on sensors, virtual sensors, calculations, models, engine conditions, or other means. The flow conditions are run through the thermal model of the DPF 102 to create a result that estimates the temperature out of the DPF 102. This thermal prediction is then compared to the actual thermal response of the DPF 102 measured by sensor 112.

[0038] In one embodiment of the present invention to be described in association with FIG. 2, soot loading information of the DPF 102 of FIG. 1 is determined from such a comparison. In this embodiment, the predicted temperature out of the DPF 102, illustrated by trace 200 in FIG. 2, is predicted using the thermal model based on the properties of a clean DPF 102, i.e. one without any soot. During a regeneration event of an operating DPF 102 with the input temperature illustrated by trace 204, the measured temperature from sensor 112, illustrated by trace 202, will be higher than the predicted temperature illustrated by trace 200 if there is an exothermic reaction of the soot in the DPF 102. The predicted temperature (trace 200) and measured temperature (trace 202) out of the DPF 102 are passed to a state machine to determine the behavior of the DPF 102. If the measured temperature (trace 202) is above the predicted temperature (trace 200), a regeneration event is occurring or has occurred.

[0039] Preferably, embodiments of the present invention determine other factors about the DPF 102 condition by examining these two traces 200, 202. As discussed above, the

regeneration event is initiated when an initiation algorithm such as known in the art, determines that the desired soot loading level has been reached for the DPF 102. Such an algorithm may also be referred to as a soot loading algorithm. Once this regeneration event has occurred, the system and method of an embodiment of the present invention calculates an integrated difference of the temperature data, illustrated in one form as temperature profiles (traces 200, 202) generated for the regeneration event. The temperature data, predicted/estimated or actual, may be in the form of temperature profiles or individual data points depending on the implementation of the various embodiments of the present invention. This integrated difference correlates to the amount of soot that is oxidized in the DPF 102. Therefore, the measured magnitude of this exothermic reaction may be used in one embodiment to assist or adjust the conventional soot loading algorithm for predicting soot loading of the DPF 102. That is, this information is used to correct the predicted value of soot in the DPF 102 or to help determine the accuracy of the soot loading predictions made by the conventional soot loading algorithm. In other words, if the measured amount of exothermic energy, i.e. temperature rise, is different than a predicted amount of energy or temperature rise, the soot loading algorithm is not accurately predicting the soot loading of the DPF 102.

[0040] Such information may then be used by such algorithms to adjust when they command future initiations of the regeneration process. This integrated difference provides a measurement for how much soot was consumed by the regeneration event. The measurement of soot consumed by the regeneration event can also be used to update or provide a check on the accuracy of algorithms that are constantly tracking the soot levels extracted from the exhaust gas by the DPF 102.

[0041] If more energy is generated during the regeneration process than is predicted, the conventional soot loading algorithm is not predicting a sufficient amount of soot loading and is actually not initiating the regeneration process at the correct time. Instead, the soot loading algorithm is initiating the regeneration process too late such that the DPF 102 becomes more loaded with soot than desired. Thus, using this information, the soot loading algorithm can be calibrated to determine that the DPF 102 is loading with soot quicker than the original soot loading algorithm predicted such that regeneration is initiated sooner and thus more accurately. In operation, the soot loading algorithm may be accelerated so as to predict more rapid soot loading of DPF 102.

[0042] Similarly, if less energy is actually produced during the regeneration, the soot loading algorithm could be calibrated in the opposite manner such that the algorithm will be

retarded such that it determines that soot is being loaded at a slower rate. Thus, the algorithm will be calibrated to ultimately delay initiation of the next regeneration such that regeneration occurs at the desired level of loading.

[0043] FIG. 5 is a flow chart of an operation of this embodiment of the invention for use in calibrating a soot loading algorithm. First, the soot loading algorithm will predict that the DPF 102 has been loaded with a sufficient amount of soot and initiate a DPF regeneration 220. During the regeneration of the DPF 102, the system controller 108 will gather information 222 from sensors 110 and 112 regarding the DPF regeneration process, particularly the temperature of the gas coming out of DPF 102. The gathered data will be compared to predicted data to determine if the soot loading algorithm is calibrated correctly 224. More particularly, a predicted amount of energy would be determined based on the amount of predicted soot loaded into DPF 102 and the actual amount of soot removed from the DPF as a result of the exothermic regeneration process. If the energy that is actually produced during the regeneration correlates to, e.g. is equal to, the predicted amount of energy from the predicted level of removed soot, the soot loading algorithm will be considered to be calibrated correctly and the system will wait 225 for the next DPF regeneration initiation.

[0044] If it is determined the soot loading algorithm is not calibrated correctly at step 224, the system will determine if the soot loading algorithm needs to be retarded or accelerated 226. More particularly, if the actual energy produced is greater than a predicted amount of energy, the soot loading algorithm will be accelerated 228 so that the soot loading algorithm predicts more rapid loading of the DPF 102. If the actual energy produced is less than a predicted amount of energy, the soot loading algorithm will be retarded 230 so that it predicts slower loading of the DPF 102. After calibrating or otherwise modifying the soot loading algorithm 228, 230, the system will return and wait 225 for the next initiation of a DPF regeneration.

[0045] With reference to FIGS. 3 and 6, in another embodiment, calibration of the thermal model is provided. Periodically, it may be necessary to calibrate or check the calibration accuracy of the thermal model to determine if it is accurately predicting the output temperature of the DPF 102. This is performed on a regular basis in one embodiment. The first step of this method performs an enhanced regeneration process 320. The enhanced regeneration process 320 utilizes a longer duration and higher temperature than a normal regeneration. Such an enhanced regeneration helps ensure that the DPF 102 has been cleaned of soot as much as possible. It should be noted that in other

implementations, an enhanced regeneration need not be implemented, but that a standard regeneration could be utilized in the event that the system cannot execute an enhanced regeneration. In such an installation, an enhanced regeneration shall be a normal regeneration unless expressly distinguished by one of the above identified characteristics of higher temperature or longer duration.

[0046] Once the enhanced or initial regeneration process 320 has been completed, the next step of the method is generation of a thermal pulse 322 which sends a short duration pulse of temperature (illustrated as trace 300 in FIG. 3) through the DPF 102 from the heat addition device (e.g. burner 104 in FIG. 1 or a modified engine operation). Because the DPF 102 is in a "clean" condition, the measured temperature profile (illustrated as trace 302 in FIG. 3) can then be used to re-calibrate the model or means of estimating the output temperature (the estimate illustrated as trace 304 in FIG. 3), which is a prediction of the "clean" in-service DPF's response to thermal inputs.

[0047] The temperature out of the DPF 102 is monitored 324 at sensor 112 in response to the thermal pulse. This monitored temperature is compared to predicted temperature values 326. If the monitored temperature profile correlates to the predicted temperature data, then no calibration is needed and the system returns and waits 327 for the next initiation of this form of calibration. If not, the system will proceed to determine how to calibrate the thermal model 330.

[0048] If the monitored temperature data is greater than the predicted temperature data, then the thermal model is modified such that it predicts an increased temperature data 328. If the monitored temperature data is less than the predicted temperature data, then the thermal model is modified such that it predicts a decreased temperature data. After proper calibration of the thermal model, the system then awaits 327 for the next initiation of this method of calibration, e.g. initiation of an enhanced DPF regeneration.

[0049] In another embodiment this method may be used by the original equipment manufacturer (OEM) on a production or new system to allow the regeneration algorithm to do a self-calibration of the temperature algorithm. The process would be substantially similar to the previous process. However, the initial enhanced regeneration step 320 is not needed as the DPF 102 would already be in a clean state as the system is new. The ability to do self-calibrations with new hardware allows the use of lower accuracy sensors and will allow more variation in system components, resulting in a cost savings to the OEM. For instance, if the temperature out sensor 112 was not perfect, the calibration step would

compensate for the mis-calibration of the sensor 112 by adjusting the thermal model according to the reading of sensor 112.

[0050] This comparison of subtle changes between the predicted DPF 102 response and the actual response could also provide soot loading information about the filter. Thus, the temperature out information, such as illustrated for example in FIG. 3, could also depict a thermal event caused by normal or forced engine 106 operational conditions. Trace 300 represents the engine exhaust temperatures while trace 304 represents the predicted clean DPF 102 response. Trace 302 represents the measured response that results from the accumulated soot in the DPF 102 changing the thermal response of the DPF 102 system. The difference between trace 302 and trace 304 could be correlated to the soot loading level in the DPF 102 and used as an input to determine the proper time to initiate regeneration. The test pulse, as illustrated in FIG. 3, could result from an auxiliary heat addition device 104 or the engine 106, as discussed above.

[0051] A method of using a thermal pulse as a means for determine when to initiate a regeneration will follow with reference to FIG. 7. First, a thermal pulse will be generated 350. The temperature out at sensor 112 will be monitored 352. Then, the temperature out will be compared to a predicted threshold temperature out 354. The predicted threshold temperature out is correlated to a threshold level of soot loading at which a regeneration needs to be initiated. If the actual temperature out is less than the predicted threshold temperature then the system will initiate a DPF regeneration 356 as it will be determined that a sufficient amount of soot loading has occurred. However, if the actual temperature out is greater than or equal to the threshold temperature, then the system will not initiate a DPF and will return and wait 357 for the next time that a soot loading analysis need be performed.

[0052] It should be noted that most of these different methods can be combined together. For one example, the soot loading calibration method illustrated with reference to FIG. 2 and 5 can be used to adjust the predicted threshold temperature of the previous method. If the soot loading calibration method above determines that regeneration initiation is occurring to late, the predicted threshold temperature out value could be calibrated accordingly after such a soot loading calibration has been performed.

[0053] In another embodiment of the present invention, the system and method provide tracking of soot loading of the DPF 102, i.e. the temperature calibration methods can also be used as a diagnostic tool. In this embodiment, the error between the "clean" filter data and

the temperature estimate based on the old, initial or previous calibration can be tracked to determine several factors. For example, it is common for a DPF 102 to accumulate soot in the outer layers that cannot be regenerated due to thermal conduction to the packaging of the DPF 102. In other words, the radially outer portion of the DPF 102 may be too cool to regenerate due to thermal conduction in these regions. Because this layer of soot could change the actual thermal response of the DPF 102, the change in the calibration of the thermal data monitored in this embodiment can be monitored and can be used to indicate that maintenance is required to clean the DPF 102.

[0054] In another example, the system and method can track another DPF parameter, i.e. ash loading that will also require service on the DPF 102. As more ash accumulates in the DPF 102, the thermal response of the DPF 102 will change. When the current calibration, i.e. the current thermal data estimate generated by the thermal model, reaches a predetermined difference from a benchmark value, e.g. the initial, previous or threshold calibration values or data, the system and method of the present invention determines that ash has accumulated to levels requiring maintenance of the DPF 102 and ash removal. This may be particularly true when comparing the temperature data after an enhanced regeneration because the ash will not be removed during an enhanced regeneration process. For typical DPF's, the actual thermal data that will be generated from actual data collected by sensor 112 will typically decrease as ash accumulates.

[0055] An embodiment of this method is illustrated in FIG. 8. The method first includes initiation of a regeneration or a thermal pulse 360. The temperature out data at sensor 112 is monitored and gathered 362. Next, the difference between the temperature out data and a benchmark value is determined 364. This difference may be expressed in numerous formats. For example, but not limiting, the difference may be expressed as an actual temperature difference or as a percentage value. The difference is then compared to a predetermined or allowable difference 366. If the difference is less than the predetermined or allowable difference, then the DPF 102 does not need maintenance and it will just wait 367 for the next regeneration. If the difference is greater than or equal to the predetermined or allowable difference, then the DPF 102 needs maintenance and the system will initiate an alarm or other signal 368 to operably communicate this condition to an operator.

[0056] In one embodiment of the present invention using the previous method, the system and method may also be able to detect damage that may have occurred to the DPF 102. In this embodiment the calibration information, i.e. the thermal data of the measured input, measured output, and estimated output temperatures, is used and the magnitude of the

difference between the estimated and measured output temperature data is determined. Damage of the DPF 102 or failure of the filtration system may be detected by a change in calibrations, i.e. the difference between the measured and predicted output temperature data, is over a pre-determined threshold, e.g. a $> 20\%$ change in calibration values. In other words, if there is a large change required to the calibrations in order to make the output temperature prediction accurate again, then it is likely that some part of the filtration system is not functioning correctly. In one implementation, during the comparison step 366, the system could compare the difference against two different benchmark difference numbers. A first benchmark difference value could be about 20%, as noted above. However, a second benchmark difference value could be about 30%. If it is determined that the difference is greater than 20% but less than 30%, maintenance is signaled at step 368. However, if the difference is greater than 30% then failure or significant damage could be signaled.

[0057] Alternatively, in the event that the DPF 102 has been significantly damaged due to cracking or melting, a characteristic response of the output temperature may be present. If the filter channels are less restrictive due to the damage, the temperature response (illustrated as trace 400 in FIG. 4) measured at the output of the DPF 102 in response to a temperature input pulse (illustrated as trace 402 in FIG. 4) may be significantly faster and greater than as predicted (illustrated as trace 404 in FIG. 4) by the thermal model. This is because the damaged area of the DPF 102 allows hot gases to slip through the DPF 102 at a more accelerated rate than if the DPF 102 were not damaged. By monitoring the difference between a predicted temperature output (trace 404) and a measured temperature output (trace 400), damage to the DPF may be detected. In one implementation, steps 364 and 366 of the previous method could be modified to compare temperature response of the DPF 102 to a theoretical or benchmark temperature data rather than directly analyzing the differences. For instance, in one implementation, the slope of the temperature data could be compared to a benchmark slope. Similarly, the amount of time it takes to reach a predetermined temperature value could be analyzed. Therefore, if it takes less than a predetermined or benchmark amount of time to reach the predetermined temperature value, then it could be determined that the DPF 102 is damaged. This could be beneficial in systems where an actual temperature value difference may not be observed, but merely the time at which a given temperature value is reached is different than when compared to a clean and properly working system or when compared to the thermal model.

[0058] All references, including publications, patent applications, and patents cited herein are hereby incorporated by reference to the same extent as if each reference were

individually and specifically indicated to be incorporated by reference and were set forth in its entirety herein.

[0059] The use of the terms “a” and “an” and “the” and similar referents in the context of describing the invention (especially in the context of the following claims) is to be construed to cover both the singular and the plural, unless otherwise indicated herein or clearly contradicted by context. The terms “comprising,” “having,” “including,” and “containing” are to be construed as open-ended terms (i.e., meaning “including, but not limited to,”) unless otherwise noted. Recitation of ranges of values herein are merely intended to serve as a shorthand method of referring individually to each separate value falling within the range, unless otherwise indicated herein, and each separate value is incorporated into the specification as if it were individually recited herein. All methods described herein can be performed in any suitable order unless otherwise indicated herein or otherwise clearly contradicted by context. The use of any and all examples, or exemplary language (e.g., “such as”) provided herein, is intended merely to better illuminate the invention and does not pose a limitation on the scope of the invention unless otherwise claimed. No language in the specification should be construed as indicating any non-claimed element as essential to the practice of the invention.

[0060] Preferred embodiments of this invention are described herein, including the best mode known to the inventors for carrying out the invention. Variations of those preferred embodiments may become apparent to those of ordinary skill in the art upon reading the foregoing description. The inventors expect skilled artisans to employ such variations as appropriate, and the inventors intend for the invention to be practiced otherwise than as specifically described herein. Accordingly, this invention includes all modifications and equivalents of the subject matter recited in the claims appended hereto as permitted by applicable law. Moreover, any combination of the above-described elements in all possible variations thereof is encompassed by the invention unless otherwise indicated herein or otherwise clearly contradicted by context.

WHAT IS CLAIMED IS:

1. A method of detecting conditions of a diesel particulate filter (DPF) used in the exhaust system of a diesel engine, the exhaust system including a heat addition device for initiating a regeneration of the DPF, the heat addition device being controlled by a controller programmed with a regeneration algorithm that determines when to initiate the regeneration process, at least one sensor is coupled to the controller for monitoring input characteristics of exhaust entering the DPF including at least one temperature sensor for monitoring an input temperature of the exhaust entering the DPF and at least one sensor for monitoring an output temperature of the exhaust exiting the DPF, the method comprising the steps of:

determining estimated thermal exit temperature data of the exhaust exiting the DPF based at least in part on the input characteristics of the exhaust entering the DPF;

measuring the output temperature data of the exhaust exiting the DPF to determine actual thermal exit temperature data of exhaust exiting the DPF;

comparing the estimated thermal exit temperature data to the actual thermal exit temperature data to determine a difference therebetween; and

determining the condition of the DPF by analyzing the difference.

2. The method of claim 1, further comprising the step of:

initiating a regeneration of the DPF; and

wherein the step of analyzing comprises the steps of:

integrating the difference between the estimated thermal exit temperature data and the actual thermal exit temperature data to determine an amount of soot burned during regeneration; and

adjusting an initiation of a subsequent regeneration based on the amount of soot burned during the regeneration relative to a predicted amount of soot burned during the regeneration.

3. The method of claim 2, wherein the step of adjusting comprises the step of retarding initiation of the subsequent regeneration when the amount of soot burned is less than a predetermined amount and the step of adjusting comprises the step of accelerating initiation of a subsequent regeneration when the amount of soot burned is greater than a predetermined amount.

4. The method of claim 2, wherein the controller is programmed with a soot loading algorithm configured to determine when to initiate regeneration of the DPF by

predicting soot loading of the DPF, and wherein the step of adjusting comprises adjusting the soot loading algorithm to retard the soot loading algorithm to determine slower soot loading and thus retard initiation of the next regeneration when the amount of soot burned is less than a predetermined amount and comprises adjusting the soot loading algorithm to accelerate the soot loading algorithm to determine quicker soot loading and thus accelerate initiation of the next regeneration when the amount of soot burned is greater than a predetermined amount.

5. The method of claim 1, further comprising:
initiating an enhanced regeneration of the DPF to establish a baseline clean condition of the DPF;
after completion of the enhanced regeneration, applying a heat pulse to the DPF;
determining the estimated thermal exit temperature data of the exhaust exiting the DPF based at least in part on the input temperature of the exhaust entering the DPF during the heat pulse;
measuring the output temperature of the exhaust exiting the DPF during the heat pulse to determine actual thermal exit temperature data of the exhaust exiting the DPF during the heat pulse;
comparing the estimated thermal exit temperature data during the heat pulse to the actual thermal exit temperature data during the heat pulse to determine a calibration difference therebetween; and
calibrating the step of determining estimated thermal exit temperature data of exhaust exiting the DPF during a subsequent process based on the calibration difference.

6. The method of claim 5, wherein the step of calibrating includes calibrating a thermal model of the DPF used during the step of determining the estimated thermal exit temperature profile of the exhaust exiting the DPF based on the calibration difference.

7. The method of claim 1, wherein the step of analyzing the difference to determine the condition of the DPF comprises the step of providing an indication that maintenance of the DPF is required when the difference indicates that the actual thermal exit temperature data is different than the estimated thermal exit temperature data by a predetermined amount.

8. The method of claim 1, wherein the step of analyzing the difference to determine the condition of the DPF comprises the step of providing an indication that damage to the DPF has occurred when the difference indicates that at least a portion of the

actual thermal exit temperature data has a rate of change that is different than a rate of change of a corresponding portion of the estimated thermal exit temperature data by a predetermined amount.

9. The method of claim 1, further comprising the steps of:
applying a heat pulse to the DPF;
determining the estimated thermal exit temperature data of the exhaust exiting the DPF during the heat pulse;
measuring the output temperature of the exhaust exiting the DPF during the heat pulse to determine actual thermal exit temperature data of the DPF as a result of the heat pulse;
comparing the estimated thermal exit temperature data during the heat pulse to the actual thermal exit temperature data during the heat pulse to determine a calibration difference therebetween; and
calibrating the step of determining the estimated thermal exit temperature profile of the exhaust exiting the DPF during a subsequent regeneration based on the calibration difference.

10. The method of claim 9, wherein the step of calibrating includes calibrating a thermal model of the DPF used during the step of determining the estimated thermal exit temperature data of the exhaust exiting the DPF based on the calibration difference.

11. The method of claim 9, wherein the steps of applying a heat pulse to the DPF and calibrating occur as a new hardware self-calibration prior to soot loading of the DPF.

12. The method of claim 1, further comprising the steps of:
applying a different heat pulse to the DPF;
determining the estimated thermal exit temperature data of the exhaust exiting DPF as a result of the heat pulse;
measuring the output temperature of the exhaust exiting DPF as a result of the heat pulse to determine the actual thermal exit temperature data of the exhaust exiting DPF as a result of the heat pulse;
comparing the estimated thermal exit temperature data during the heat pulse to the actual thermal exit temperature data during the heat pulse to determine a regeneration initiation difference therebetween; and
initiating a regeneration when the regeneration initiation difference is greater than a predetermined value.

13. A diesel particulate filter (DPF) system for removing particulates from diesel engine exhaust, comprising:

a diesel particulate filter (DPF) having an inlet and an outlet;

a heat addition device;

a DPF input temperature sensor positioned to sense temperature of fluid entering the DPF at the DPF inlet;

a DPF output temperature sensor positioned to sense temperature of fluid exiting the DPF at the DPF outlet;

a controller configured to control the heat addition device to initiate regeneration of the DPF based on a regeneration algorithm; and

wherein the controller is configured to determine estimated thermal data of the DPF based at least in part on the input temperature of the fluid entering the DPF, to measure the output temperature of the fluid exiting the DPF to determine actual thermal data of the DPF, to compare the estimated thermal data to the actual thermal data to determine a difference therebetween, and to analyze the difference to determine the condition of the DPF.

14. The system of claim 13, wherein the controller is configured to integrate the difference to determine an amount of soot burned during regeneration, and adjusts when a subsequent regeneration is initiated based on the amount.

15. The system of claim 14, wherein the controller is configured to retard determination of a initiation of a subsequent regeneration when the amount of soot burned is less than a predetermined amount and wherein the controller is configured to accelerate determination of an initiation of the subsequent regeneration when the amount of soot burned is greater than a predetermined amount.

16. The system of claim 13, wherein the controller is further configured to initiate an enhanced regeneration of the DPF to establish a baseline clean condition of the DPF, and after completion of the enhanced regeneration, to apply a heat pulse to the DPF, to determine the estimated thermal data of the fluid exiting the DPF as a result of the heat pulse, to measure the output temperature of the fluid exiting the DPF as a result of the heat pulse to determine the actual thermal data of fluid exiting the DPF, to compare the estimated thermal data to the actual thermal data to determine a calibration difference therebetween, and to calibrate the controller's configuration to determine the estimated thermal data of the fluid exiting the DPF during a subsequent process based on the calibration difference.

17. The system of claim 13, wherein the controller is configured to provide an indication that maintenance of the DPF is required when the difference indicates that the actual thermal data is different than the estimated thermal data by a predetermined amount.

18. The system of claim 13, wherein the controller is configured to provide an indication that the DPF is damaged when the difference indicates that at least a portion of the actual thermal exit temperature profile has a rate of change that is different than a rate of change of a corresponding portion of the estimated thermal exit temperature data by a predetermined amount.

19. The system of claim 13, wherein the controller is configured to apply a heat pulse to the DPF prior to determining the estimated thermal data of the DPF, to determine the estimated thermal data of the DPF based at least in part on the input temperature of the DPF during the heat pulse, to measure the output temperature of the DPF during the heat pulse to determine actual thermal data of the DPF during the heat pulse, to compare the estimated thermal data during the heat pulse to the actual thermal data during the heat pulse to determine a calibration difference therebetween, and to calibrate its configuration to determine the estimated thermal data of the DPF based at least in part on the input temperature of the DPF during the subsequent regeneration based on the calibration difference.

20. A method of detecting conditions of a diesel particulate filter (DPF), comprising the steps of:
initiating a heat pulse,
determining an estimated thermal data of fluid exiting the DPF based on the temperature of fluid entering the DPF;
measuring the output temperature of the fluid exiting the DPF to obtain actual thermal data of the fluid exiting the DPF as a result of the heat pulse;
comparing the estimated thermal data to the actual thermal data to determine a difference therebetween;
calibrating a thermal model of the DPF based on the difference.

21. The method of claim 20, wherein all steps are performed for at least a first time as a new hardware self-calibration.

22. The method of claim 20, further comprising the step of initiating an enhanced regeneration to establish a clean baseline of the DPF and wherein all steps are

performed after the step of initiating the enhanced regeneration, and the step of calibrating updates the thermal model to compensate for changes in the DPF due to particulate loading of the DPF.

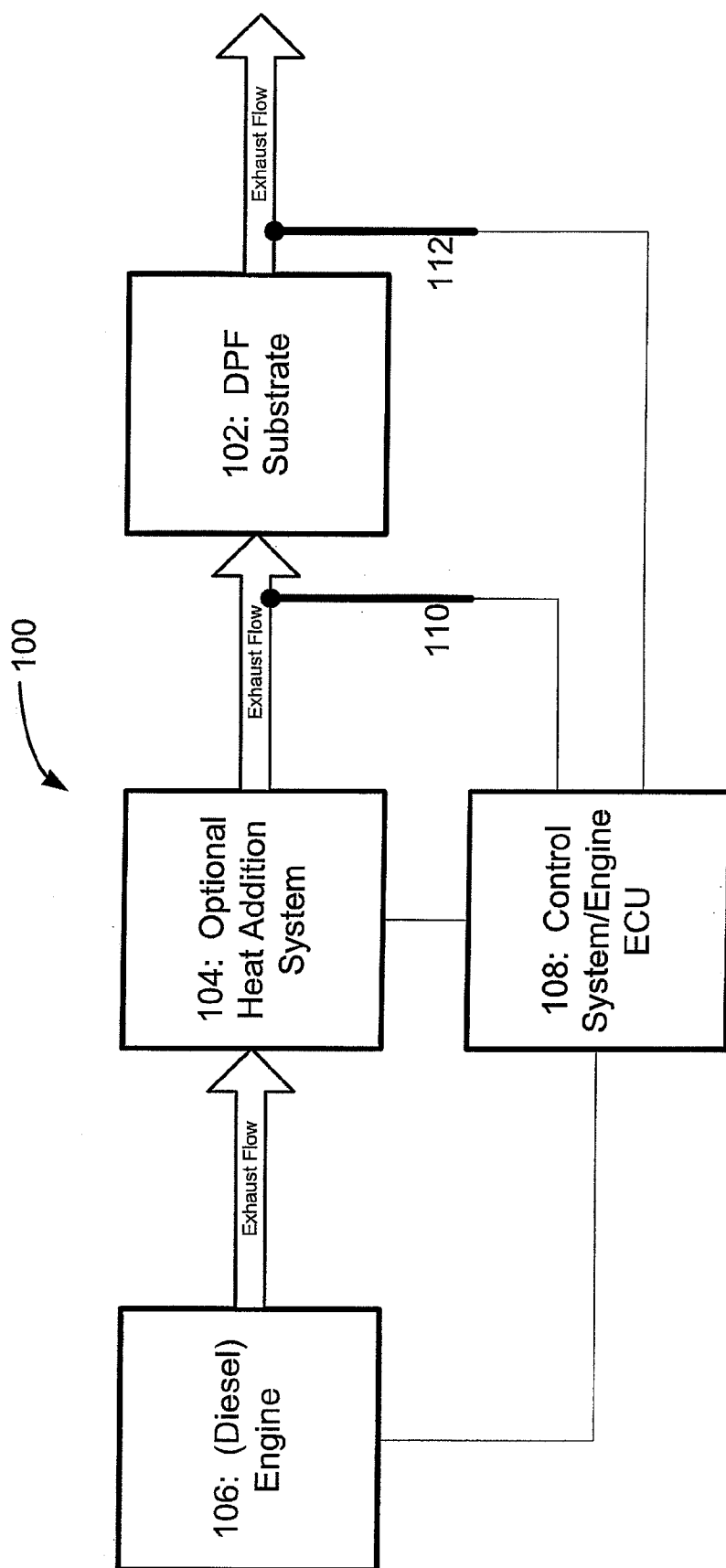


FIG. 1

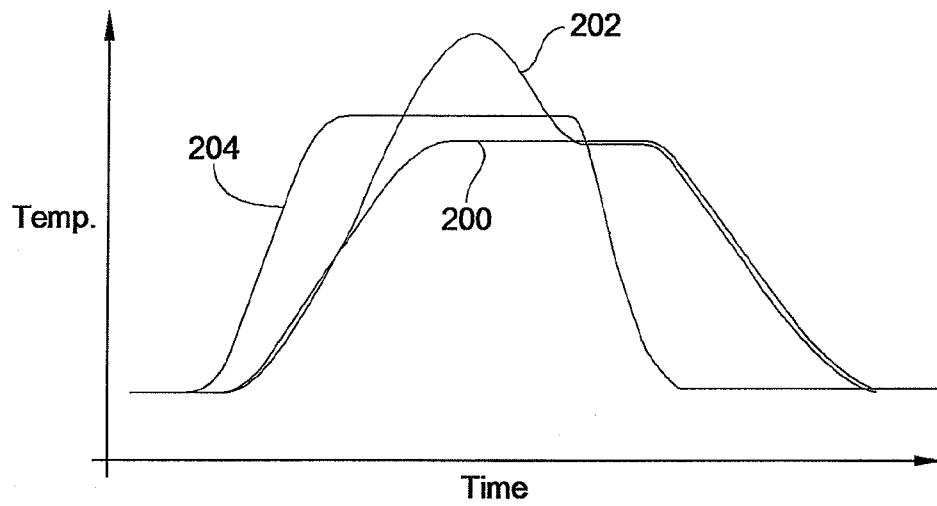


FIG. 2

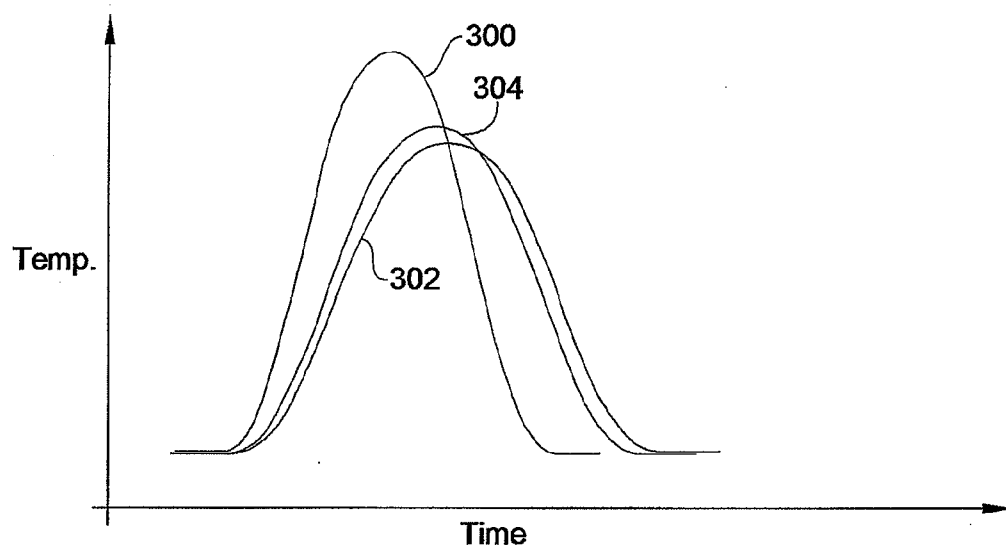
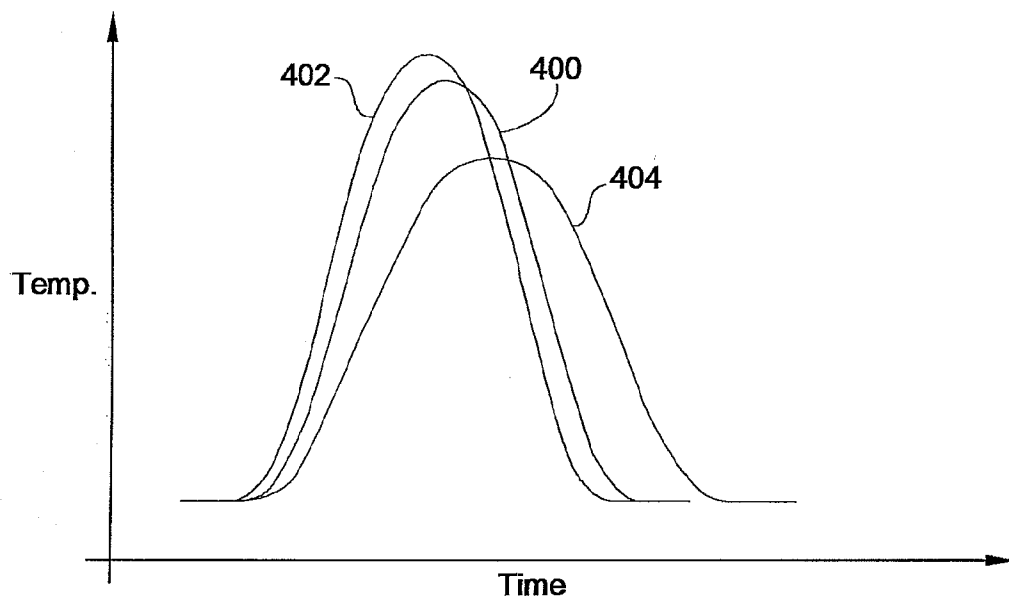


FIG. 3

**FIG. 4**

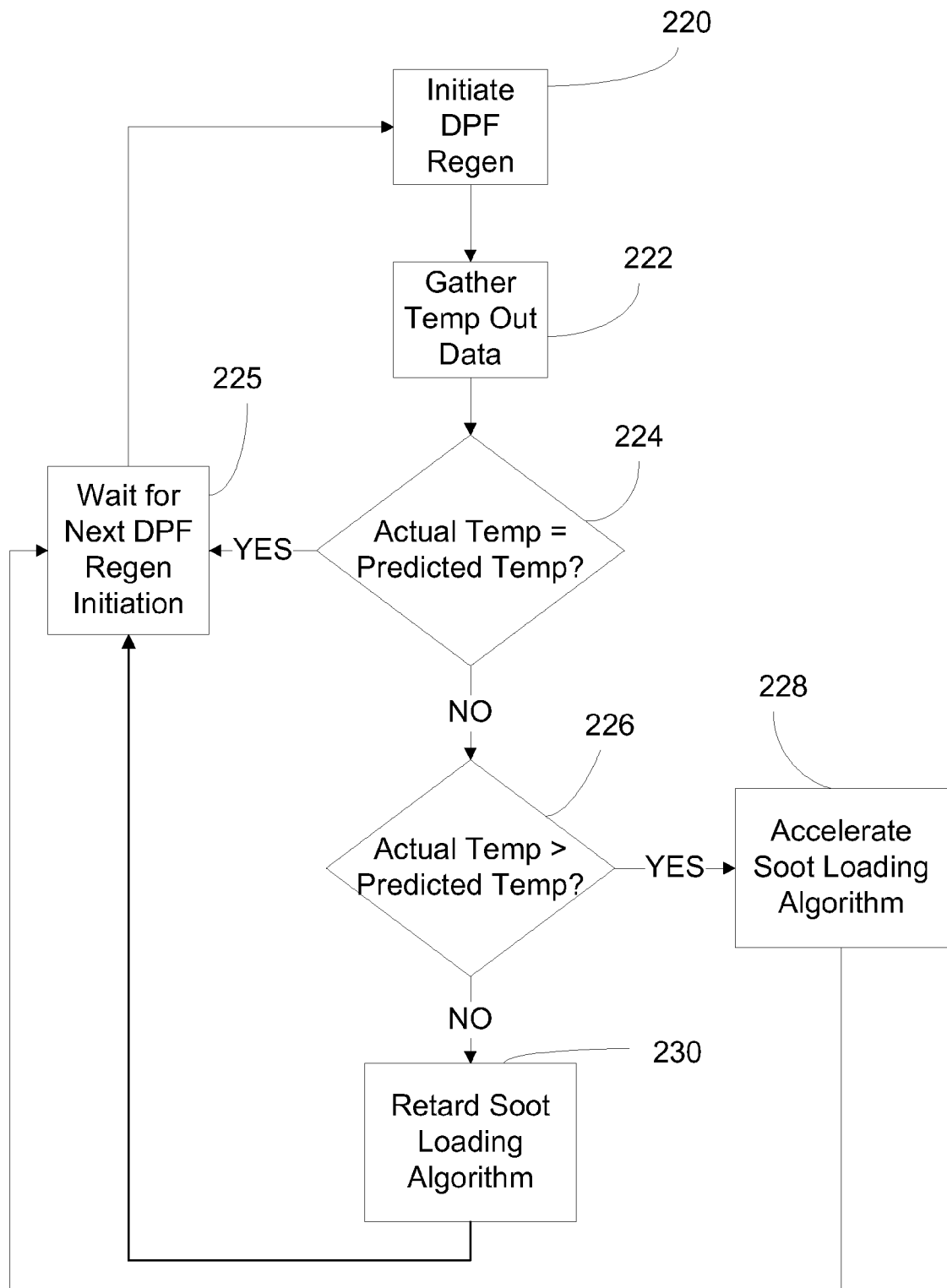
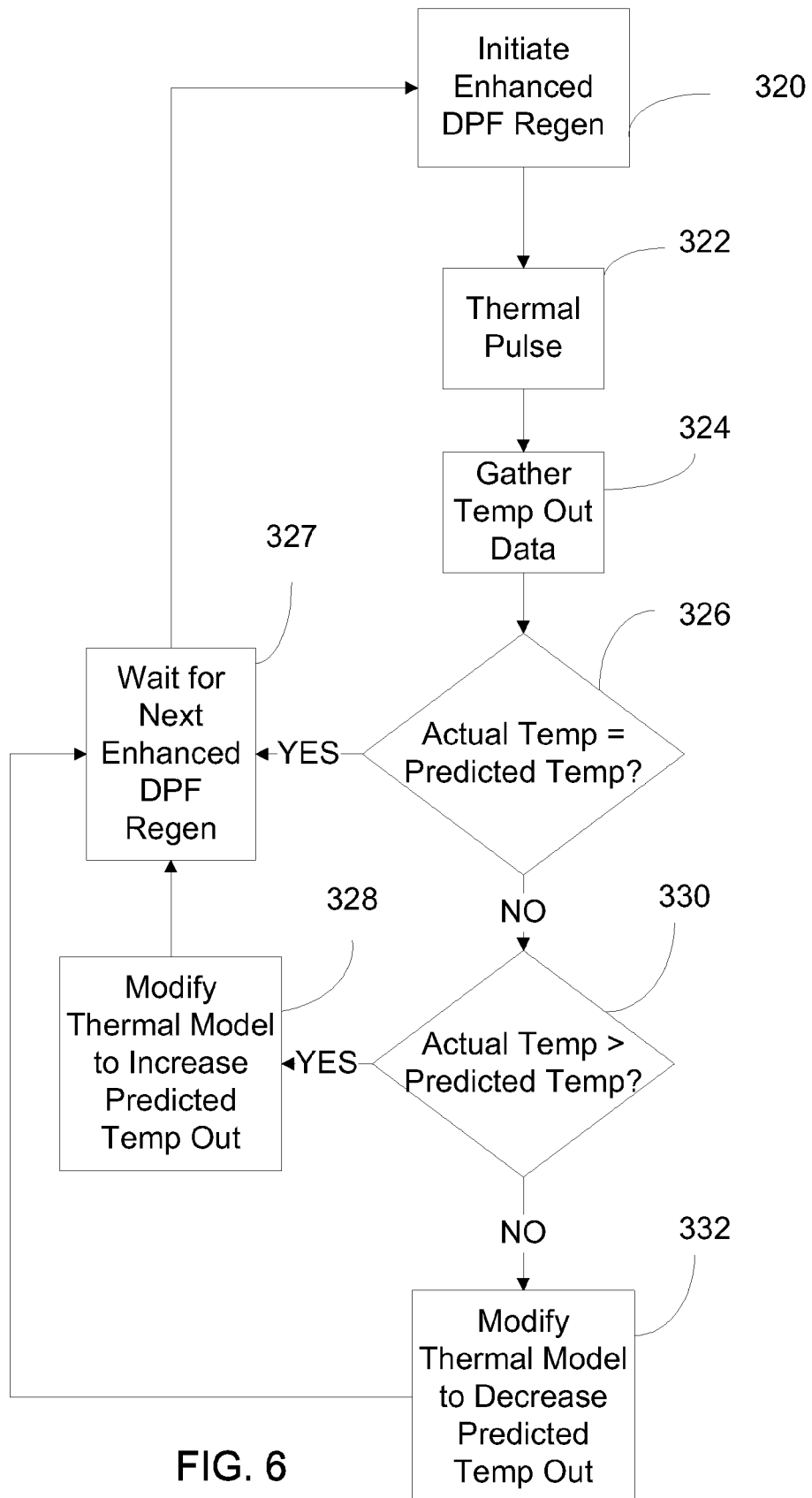


FIG. 5



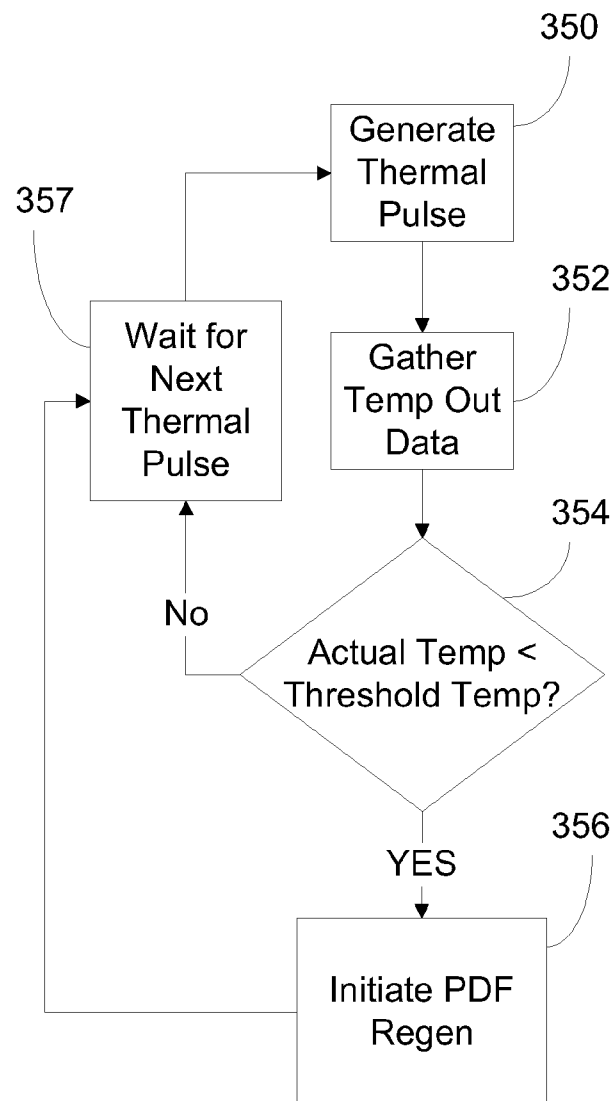


FIG. 7

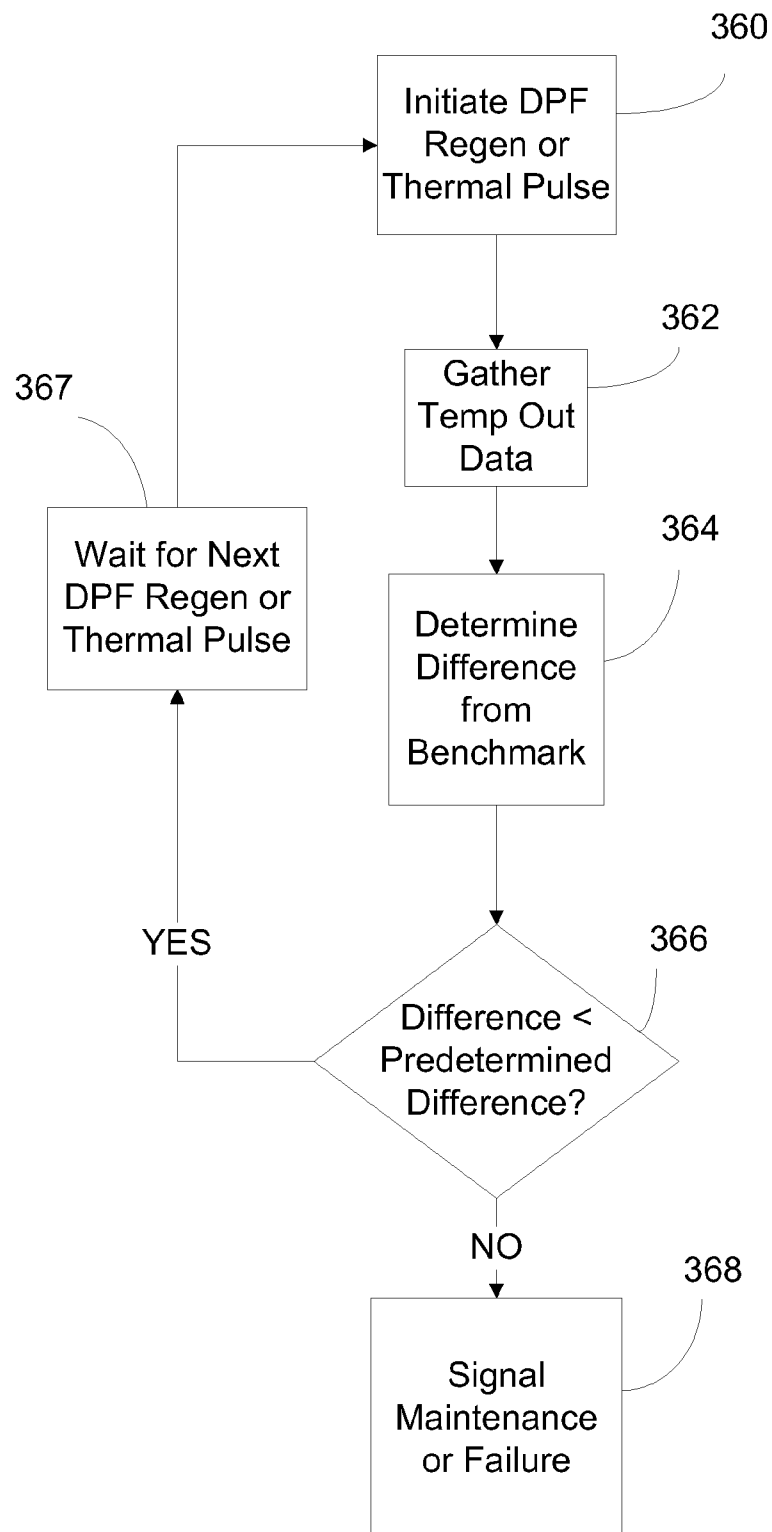


FIG. 8