JOURNAL OF PROPULSION AND POWER
Vol. 24, No. 2, March–April 2008

Investigation of Active Flow Control on Diesel Engine Aftertreatment

Ming Zheng,* Graham T. Reader,† and Meiping Wang‡
University of Windsor, Windsor, Ontario N9B 3P4, Canada

DOI: 10.2514/1.21462

Theoretical studies are performed with one-dimensional transient modeling techniques to analyze the thermal behavior of the diesel aftertreatment systems when active flow control schemes are applied. The combined use of active gas flow and active fueling-control schemes are identified to be capable of shifting the exhaust gas temperature, flow rate, and oxygen concentration to more favorable windows for the filtration, conversion, and regeneration processes. Several external fuel-supplying techniques are applied and analyzed with various heat distribution patterns and exhaust flow control parameters. The analysis indicates that the active flow control schemes have fundamental advantages in optimizing the converter thermal management that includes supplemental heating, thermal retention, thermal recuperation, and overheating protection. Modeling validation analyses with selected experiments are also reported.

Nomenclature

$\dot{m}$	=	mass flow rate, g/s
p_1	=	exhaust pressure at the inlet of an aftertreatment device
p_2	=	exhaust pressure at the outlet of an aftertreatment device
T	=	temperature, °C
T_g	=	gas-phase temperature, °C
T_{in}	=	inlet exhaust gas temperature, °C
T_m, T_{mid}	=	exhaust gas temperature in the middle of a flow-reversal path, °C
T_{out}	=	outlet exhaust gas temperature, °C
T_{1to10}	=	substrate temperatures at locations one to eight sensor points inside a converter, °C
z/L	=	relative length along the exhaust path way in the monolith (z axis in the simulation)
Δp	=	pressure difference before and after an aftertreatment device
ΔT	=	temperature difference
λ	=	air–fuel ratio

I. Introduction

DURING the past decades, diesel exhaust aftertreatment schemes with active or passive flow control are sought vigorously on the influences of gas flow, heat transfer, chemical reaction, oxygen concentration, and substrate properties [1–16]. The authors have proposed, implemented, and tested a number of active flow control schemes, including parallel alternating flow, partial restricting flow, periodic flow reversal (FR), and extended flow stagnation, that are found to be especially effective to treat modern diesel engine exhausts that are difficult to manage with conventional passive flow converters [1,3,4]. Previous work by Schenk et al. [5] has shown that significant improvements in nitrogen oxides (NOx) and particulate matter (PM) reduction by using a four-flow-path (parallel-flow) control system in the aftertreatment of a heavy-duty diesel engine. A reciprocating-flow regeneration of the diesel particulate filter (DPF) (reversal-flow) process was reported by Konstandopoulos et al. [4] to produce a cleaned filter in which a conventional regeneration was less effective. The reversal-flow processes have been used in catalytic reactors to retain the reaction temperature and to improve the emission reduction [7,8]. The benefits in the overall energy efficiency and emission reduction may overcome shortfalls of the added mechanical and control complexity in the aftertreatment systems [8].

The energy-efficiency analyses of parallel- and reversal-flow schemes have been reported previously by the authors [1,2,4]. The presented approach was active in exhaust flow control but passive in fueling control. The essence of such active aftertreatment is the flow process control in contrast to catalytic material development, although the former will be benefited from the latter, and vice versa. The objectives of such active flow control are to determine and then to reduce the critical supplemental energy, to recuperate the exhaust thermal energy with reversal-flow strategy, to adjust flow rate via flow division and throttling, and therefore to select the favorable temperature windows for the substrates. At the authors' laboratory, the active schemes (Fig. 1) were set up and developed to improve the complex thermal and chemical processes of exhaust emission reduction with various gas flow configurations.

To improve the performance of the aftertreatment devices, the exhaust gas may need to be tailored, with sacrifices in the fuel economy, either via in-cylinder combustion tampering (post injection) or supplying the external energy into the exhaust stream. In some cases, the overall energy consumption of the two approaches may come to an equivalent level [9]. However, for a prompt thermal response of the aftertreatment substrate and a minimum energy loss to the surroundings, the external supplemental energy is proven to be more effective, especially when it is applied very close to the substrate. The external fuel injection is relatively convenient to apply and is an effective substitution for internal combustion skewing.

The motivation of the present work is to develop an energy-efficient, self-regenerative disel oxidation catalyst (DOC) plus DPF system to effectively reduce diesel emissions such as carbon monoxide (CO), hydrocarbons (HC), NOx, and soot. This paper represents a methodology in active flow and fueling control that includes a model-based external fueling scheme to minimize the fuel penalty and the high temperature spikes in the aftertreatment devices (Fig. 2). The theoretical studies are performed with one-dimensional transient modeling techniques [1] that analyze the thermal behavior of the aftertreatment systems when active flow control schemes are applied.

Received 29 November 2005; accepted for publication 31 July 2007.

*Canada Research Chair in Clean Diesel Technologies, Associate Professor, Department of Mechanical, Automotive and Materials Engineering, 401 Sunset Avenue; mzheng@uwindsor.ca.

†Dean of Engineering, Professor, Department of Mechanical, Automotive and Materials Engineering, 401 Sunset Avenue.

‡Research Scientist, Department of Mechanical, Automotive and Materials Engineering, 401 Sunset Avenue.

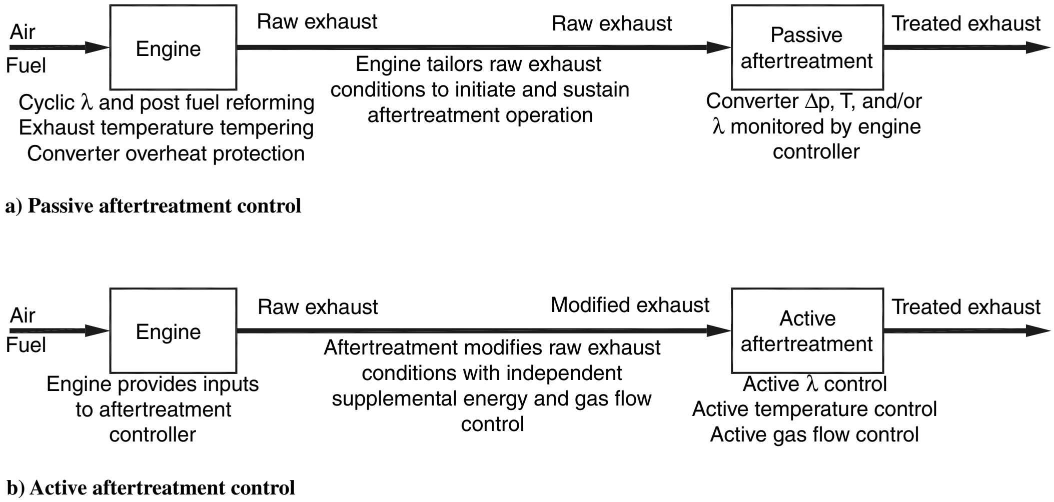


Fig. 1 Passive versus active aftertreatment control strategies.

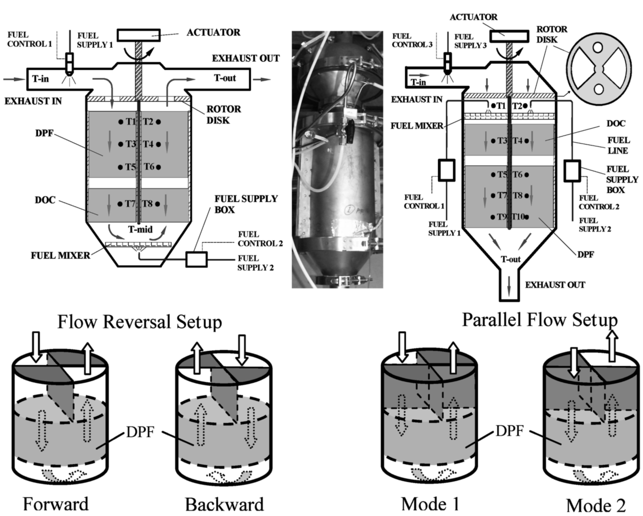


Fig. 2 Active flow control system setup and schematic diagram.

The model validation focusing on the external supplemental fuel is discussed with selected experiments herein. Several external fueling techniques are applied and analyzed with various heat distribution patterns and exhaust flow control parameters. The external fuel was delivered into the exhaust upper stream, the substrate inlet, or the central region of the substrate, corresponding to the heat distribution patterns: namely, even-, end-, and central-heat distributions in the calculations. The oxygen concentrations are assumed to be of abundance, which is justified in diesel and lean-burn engines [1,2].

II. Experimental Design in Active Flow Control

Although effective, to date, most of the advanced diesel aftertreatment measures are not sufficiently robust to warrant broad applications. The improvement in the robustness needs to be conducted at fundamental levels in an energy-efficient way, in addition to product optimizations. The common practice is to use a passive aftertreatment system that involves passive catalytic converter control and active engine fuel management control [10,11], as shown in Fig. 1a, for instance, of the control scheme typical for a passive three-way converter. However, the exhaust gas of diesel engines has a wide temperature range and is rich in oxygen, which makes conventional passive schemes less capable of energy-efficiency aftertreatment. The active flow strategies shown in Fig. 1b were developed to enhance the aftertreatment conversion efficiency of diesel engines [1,2,12].

It was anticipated through the simulation and empirical work that the active flow control system would allow the catalysts to tolerate more catalytic deactivation and to perform conversion with higher energy efficiency [12–16]. The external fueling was controlled to maintain the substrate temperature at ~600°C after the exhaust substrate was thoroughly heated. A cooling and reheating process was analyzed to reveal the effectiveness of active flow control.

An overall model-based fueling-control scheme is being developed, shown in Fig. 3, which consists of model algorithms and a real-time controller loop. A one-dimensional mathematical model of DOC and DPF regeneration was implemented. Based on the predicted temperature profile and the pressure-drop information from the simulation, the controller is programmed to maintain the optimized temperatures for DPF regeneration and to prevent excessive temperature rises [3].

III. Model-Based Control for Active Aftertreatment Systems

It has been recognized that the periodic FR oxidation is a heat trap that performs active heat recovery via monolith heat retention [1–3,7,8], By cyclically alternating the direction of exhaust flow, a thermal wave is built up that oscillates along the catalyst so that the central catalyst temperature can be elevated above the engine exhaust temperature. The FR technique has been used to facilitate DPF regeneration [2,3,7,8]. This paper provides the thermal response simulation results of the oxidation converter under the specified supplemental energy distribution patterns.

A. Simulation Assumption

Energy efficiency was defined as a measure of the overall energy penalty to the entire engine system, resulting from the need to provide the supplemental energy solely to enable and/or to improve the aftertreatment operations. The simulation is a continuous research of the previously reported work [1]. CH_4 in the working fluid serves as a representative quantity of the combined exhaust total hydrocarbon (THC) and CO in average diesel and lean-burn gaseous fuel engines for simulation simplicity. The numerical simulation is also conducted by using a one-dimensional oxidation converter model reported previously [1,6,14–16]. The convection heat transfer between the exhaust gas and the substrate, the conduction heat transfer along the walls of the substrate channels, and the supplemental energy released from the external sources are described in the model of [1]. The oxygen is assumed sufficient for the reactions and all the reaction heat from the fuel is released completely to the monolith. Several energy-release distribution patterns are selected to characterize the empirical tests.

Particularly, the fuel exothermic reactions that distribute on the monolith interior surfaces are represented with six idealized patterns having the same amount of total supplemental energy, symbolized as shown later, in respect to the inception of the external fuel and FR

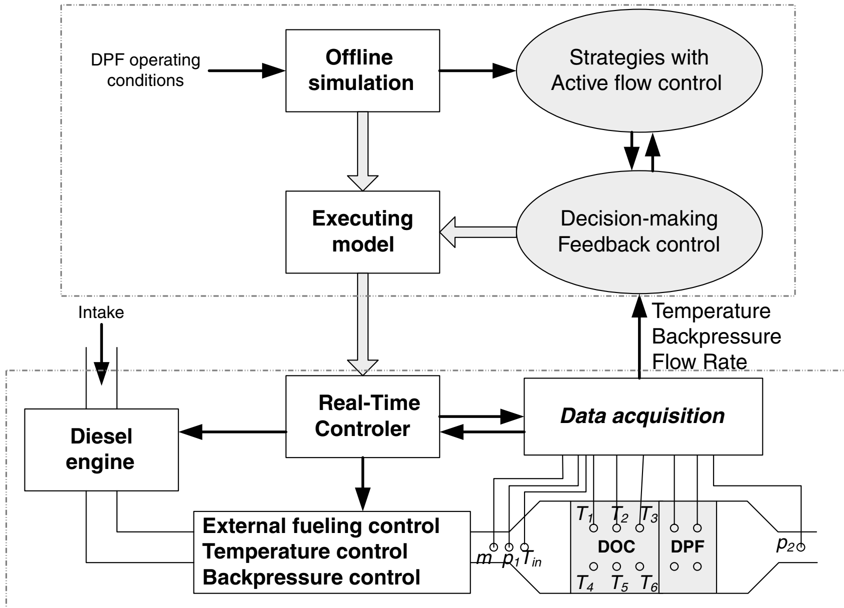
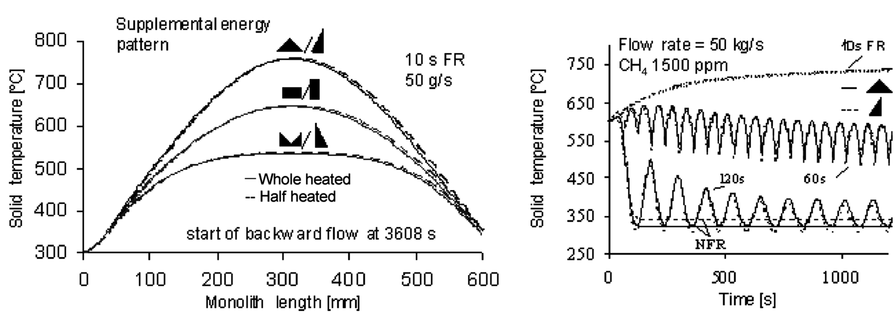


Fig. 3 A model-based active aftertreatment control scheme.



a) Six heat distribution patterns at the start of backward flow

b) With various FR flow frequencies

Fig. 4 Temperature histories with heat distributed.

strategies. The half and whole monolith heating correspond to heating either each or both of the two half-cylindrical-shaped monolith segments inside the FR converter in Fig. 2. In this simulation, the gas flow rates were selected from 10 to 100 g/s. To determine the thermal behavior of DOC flow-reversal control, a transient cooling process was applied. The simulation starts at the transition when the inflow working fluid starts cooling from 600 to 300°C, which time is defined as zero. Before the cooling, the monolith solid is thoroughly heated by the engine exhaust or external energy sources. The monolith properties applied to the substrate are the same as described in [1].

The even-heat patterns denotes that the supplemental energy amount is evenly distributed everywhere in the substrate. The central-heat pattern denotes that the central part of the substrate receives the maximum supplemental energy that declines to zero linearly at the ends of the substrate. The end-heat pattern shows that the supplemental energy is supplied from both ends of the substrate that receives the maximum rate of heat addition and declines to zero linearly toward the central region.

B. Simulation Results and Discussions

The 1-D monolith solid and gas temperature profiles and their dynamic history are analyzed here. Because the solid and gas thermal profiles show close trends throughout the simulation, the solid thermal profile will be described in the present paper. When the engine load reduces, substrates start the cooling process in which the monolith was thoroughly heated initially. The substrate temperature profiles are analyzed based on the influences of the heat distribution patterns, FR switching frequencies, exhaust flow rates, and supplemental-fueling concentrations. Parallel-flow simulation results reported previously are briefly discussed here for comparison.

1. Thermal Profiles with External Supplemental Energy in Flow-Reversal and Non-Flow-Reversal Operations

To evaluate the specific nonuniform heating pattern, the substrate temperature profiles from heating the half or whole monolith during cooling processes were compared in the following analyses.

a. Temperature Profile with External Heat Distributed to Half Versus Whole Substrate. In a periodic FR operation, when the monolith is thoroughly heated, insignificant differences were found in Fig. 4 between supplying external energy to the half or whole monolith in spite of FR frequency changes, because eventually the frequent FR cycling operations bring both halves of the monolith to similar thermal states. However, the substrate temperature may increase at the early stage of the cooling process. In a non-flow-reversal (NFR) operation (shown in Fig. 4b), the heat distributed to half of the substrate is equivalent to reduce the flow length to half and double the heat distributed with the same amount of external fueling, hence resulting in a slightly higher substrate temperature. Such observation suggests for a unipass converter (NFR) that heating half of the monolith (via substrate inlet fueling) may be more efficient than heating the whole monolith electrically or through other means.

b. Temperature Profiles in Various Supplemental Energy Patterns. The temperature histories resulted from even, central,

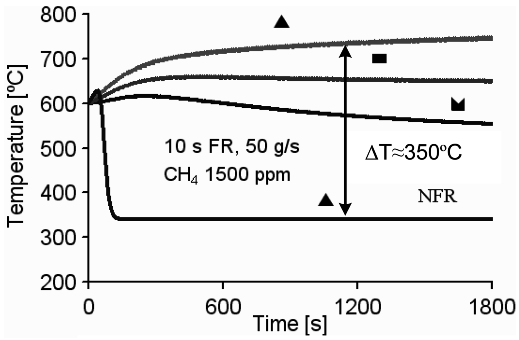


Fig. 5 Central substrate temperature in 1 h with three heat distribution patterns (one FR cycle).

and end energy distributions show stark contrast in FR operations. In Fig. 5, the combined effect of flow reversal, exothermic reaction, and solid heat retention results in a central monolith temperature rise of 400, 250, and 150°C, corresponding to central, even, and end energy patterns, respectively. Comparing to NFR, or less the exothermic temperature rise, an increment of $\Delta T \approx 350°C$ in the central fueling is produced from exhaust energy recovery, even if considering the extended duration of the low-temperature inflow (Fig. 6). The supplemental energy delivered to the middle of the substrate is clearly an effective way to raise the substrate temperature and to maintain the substrate temperature for the longest duration. The external energy efficiency in terms of the critical energy that is required to raise the substrate temperature therefore is improved simply by changing the energy dispersion locations. Such phenomena in FR have many practical implications; for instance, a central-zoned catalyst may retain the reactive temperature for a longer time in reversal-flow operations despite engine load decreases.

c. Temperature Profiles with Various Exhaust Flow Rates. Figure 6 shows the substrate temperature histories of the central region at various exhaust flow rates with two external fuel concentrations. Although a higher exhaust flow rate accelerates the substrate cooling in general, the external fueling rate is set proportional to the exhaust flow rate. A low external fueling concentration cannot retain the substrate at the high temperature in respect to flow rate reductions and a FR frequency increase, because there is not enough supplemental energy to heat up the substrate (10 g/s in Fig. 6b). At the other extreme, because the external fuel concentration and the exhaust flow rate are set sufficiently high, monolith overheating may occur, resulting from the sufficient solid heating and FR heat recuperation (Fig. 6a). In the latter case, reducing the FR frequency may help to prevent the overheating. There is a critical energy threshold of the supplemental fueling for a given FR frequency and exhaust flow rate. Thus, empirical tests were designed to determine the thresholds and to maximize the external supplemental-fuel efficiency by optimizing these parameters under different engine loads.

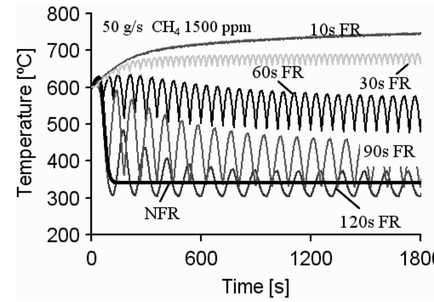


Fig. 7 Central substrate temperature histories using ▲ with various FR cycling durations.

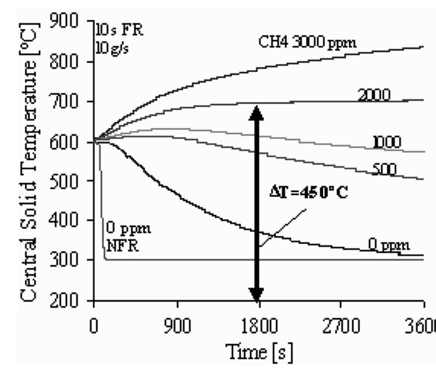
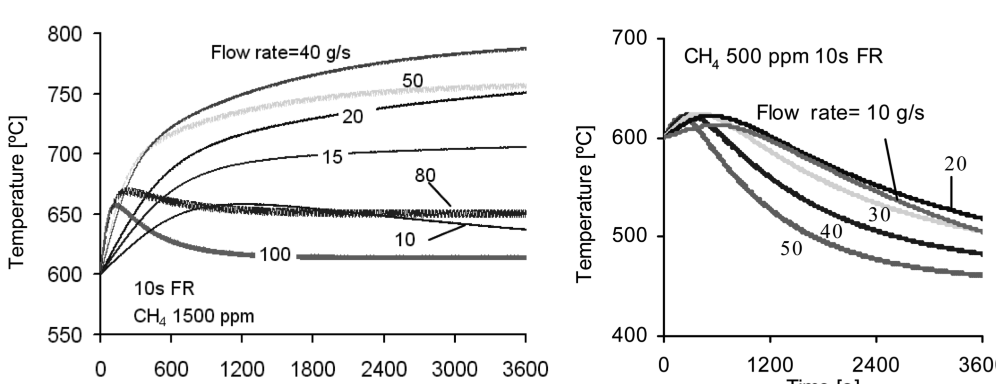


Fig. 8 Temperature histories in 1 h using central heating distribution ▲ with various concentrations of supplemental fuel.

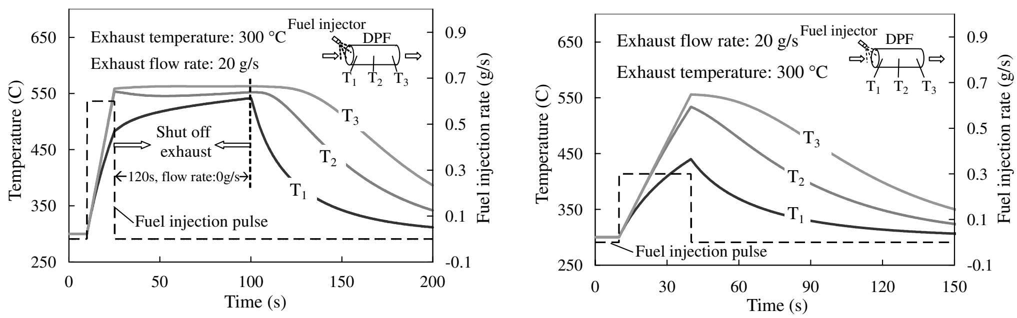
d. Temperature Profiles with Various Flow-Reversal Frequencies. Figure 7 shows the central substrate temperature histories with various FR cycling durations using the central supplemental energy distribution pattern. The shorter cycling time, or the higher switching frequency of the FR operations, provides better heat retention of the substrates. Notably, the strong effect of the heat recuperation from FR will also increase the tendency of substrate overheating. Adjusting the external fueling rate and FR frequency according to engine loads can provide a relatively simple and stable thermal state of a catalytic converter.

e. Temperature Profiles with Various External Supplemental-Fuel Concentrations. Figure 8 shows the central substrate temperature histories with various external fuel concentrations using the central supplemental energy distribution pattern. The higher the fuel concentration, the faster the monolith temperature climbs and, subsequently, the higher tendency of excessive substrate heating. At a FR frequency 10 s and a flow rate 10 g/s, 1000 ppm of an external fuel is required to maintain the substrate temperature ~600°C, which is the critical energy threshold required for this condition. Such estimation provides key feedback variables for the model-based aftertreatment control.



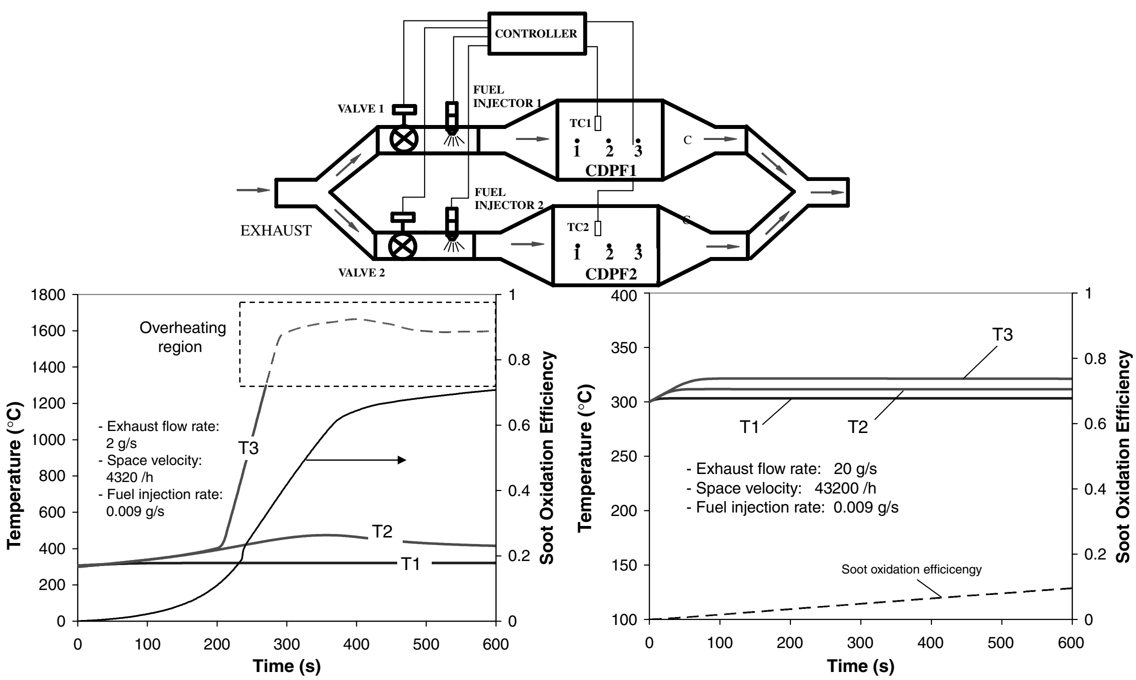
a) CH_4 = 1500 ppm **b) CH_4 = 500 ppm**

Fig. 6 Central substrate temperature histories using distribution pattern ▲ at various flow rates.



a) Flow stagnation b) Continuous flow, no flow stagnation

Fig. 9 Temperature histories of one DPF path in parallel flow with a 120-s flow stagnation (left).



a) CDPF1 = 10% exhaust flow b) CDPF2 = 90% exhaust flow

Fig. 10 Temperature histories in alternating parallel-flow operation with external supplemental-fuel injection (simulation).

2. Thermal Profiles with External Supplemental Energy in a Parallel-Flow System

The impact of parallel flow on the efficient use of a supplemental energy is demonstrated here by using a one-dimensional DPF regeneration model described previously [12,13]. The external diesel fuel injection is an effective means to modulate the substrate temperature in a parallel-flow configuration, in which a targeted branch substrate temperature can be attained without resorting to excessive external fueling. In Fig. 9a, when the exhaust flow in one path was shut off for 120 s immediately after the supplemental-fuel addition, the flow stagnation caused effective temperature rise, whereas the temperature drops quickly without flow stagnation in Fig. 9b. Such technique is particularly important for applications in catalytic DPF regenerations. Two DPF flowpaths can be alternately set to the regeneration or filtration mode. In the regeneration mode, the exhaust flow can be stopped momentarily until the desired catalytic temperature is achieved with the supplemental fueling.

By alternately changing the flow partition of each flowpath (e.g., 90 and 10% in Fig. 10) with flow rates, flow-change scheduling, and external fueling rates, a targeted temperature can be modulated steadily. Figure 10 shows some preliminary simulation results of a parallel catalytic diesel particular filter (CDPF) regeneration process. T_1, T_2, and T_3 correspond to the substrate temperatures at three marked locations. The gas flow rates in CDPF1 and CDPF2 were 10 and 90% of the engine exhaust flow rate, respectively. The overheating region was defined as the substrate temperature over 1200°C.

With the same amount of external fueling rate, CDPF2 temperature hardly reached 325°C, whereas the temperature of CDPF1 already passed the overheating mark. Such a temperature spike was eased by repartitioning the flow, increasing the exhaust flow rate, and reducing the supplemental-fueling rate. The advantages of a parallel alternating-flow DPF system are the independent regeneration control despite the engine operating conditions and the maximized supplemental-fuel efficiency during the regeneration.

Table 1 Summary of FR engine test conditions

	Test 1	Test 2	Test 3
Engine speed, rpm	1550	1550	1550
Engine torque, N · m	24.6	24.6	27.2
Smoke number (after DPF)	0.360	0.346	0.316
External fuel supply location	Center	Inlet	Inlet
External fuel injection rate, mg/s	14	14	86
External energy supply rate, kW	0.595	0.595	3.655
Maximum ΔT,[a] °C	>300	<100	>300

[a]The temperature difference between the substrate and the exhaust.

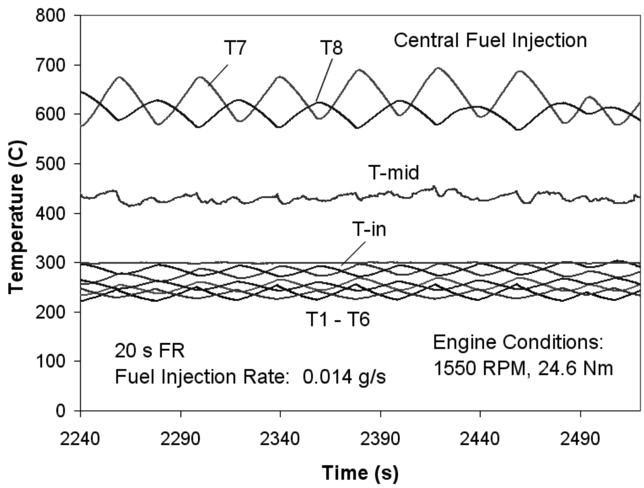


Fig. 11 Substrate temperature histories during a FR operation (central-fuel delivery, test 1).

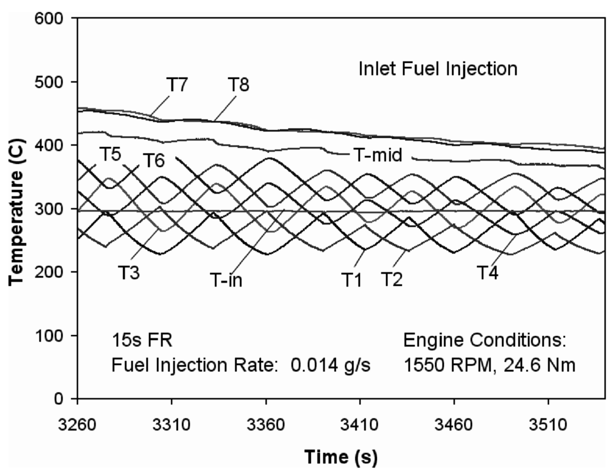


Fig. 12 Substrate temperature histories during a FR operation (inlet-fuel delivery, test 2).

IV. Empirical Results

As will be demonstrated, the preceding numerical simulations bear close resemblance to the following empirical observations. A single-cylinder Yanmar NFD-170E engine of 857-cm^3 displacement is used to generate the exhaust gas. The exhaust gas and substrate temperatures are measured by K-type thermocouples and recorded by a NI SCXI-DAQ system. The exhaust gas analyzers and the smoke meter are used for diagnostic purposes in this study.

Both the reversal-flow and parallel-flow tests were implemented on a canned substrate (DOC and DPF or CDPF) of 5.66×6 in. As an example, a pneumatic actuator is used to drive the rotor disk that directs the exhaust gas flows for either a FR system or a parallel-flow system, as shown in Fig. 2. For FR operations, the exhaust gas stream is divided into two segments by a separation plate. By swapping the rotor disc positions, the exhaust flow directions through the substrates are alternated. For parallel-flow operations, the exhaust gas stream is divided into four segments. By rotating the rotor disc, the flow mode can be changed from mode 1 to mode 2. The rotor disk is configured so that the majority of the engine exhaust goes through half of the substrate for filtration and a small amount of the exhaust goes through the other half of the substrate for regeneration, for instance. Two or three fuel injectors and a heated atomization enhancer were used to implement the assorted fuel-inject strategies.

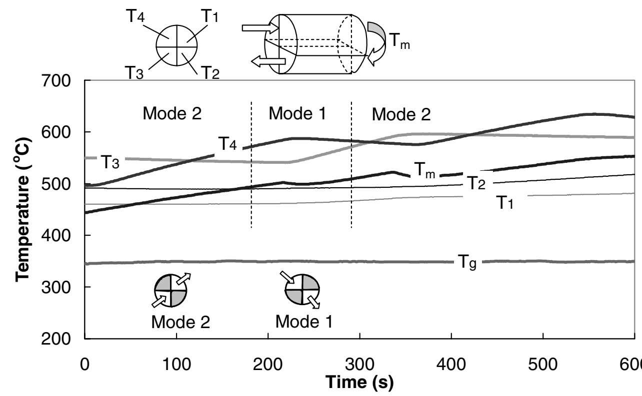


Fig. 14 Substrate temperature history in mode switching during parallel-flow processes.

A. External Supplemental-Fueling Tests

The empirical studies were conducted on a flow-reversal DPF system, shown in Fig. 2. The tests in the FR configuration are to implement the different supplemental-fuel patterns as described in the simulation, which are summarized in Table 1. The engine operating conditions and the soot emissions were kept at the same level during the tests.

Initially, the converter was heated to 600°C using external fuel injection before subjecting it to the cooling process. During the cooling process, a variety of operations were conducted to prevent the temperature from dropping below a targeted level. For the same fueling flow rate (0.014 g/s), when the fuel is delivered from the center of the flowpath, the temperature can be kept relatively stable under a fixed FR frequency; when the fuel is supplied at the inlet port of the canister, the substrate temperatures can hardly be maintained at 400°C, as shown in Fig. 11. The fuel flow rate had to be increased to 0.086 g/s (test 3) to keep the DOC temperatures over 600°C. The central-fuel delivery has drastically reduced external fuel consumption, which agrees with the simulation results closely.

B. Active Flow Control Strategy Validation

Extensive empirical tests on reversal-flow schemes have been conducted and reported previously [2,3,12,14]. For the heat-

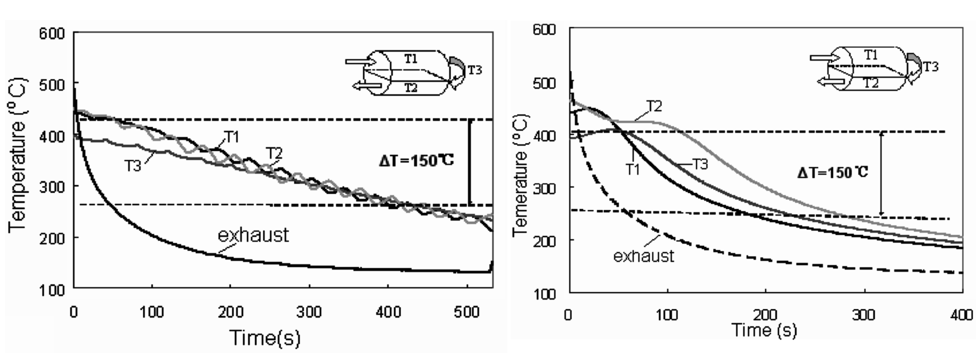


Fig. 13 Substrate thermal profile in a cooling process with (left) FR and (right) NFR operation.

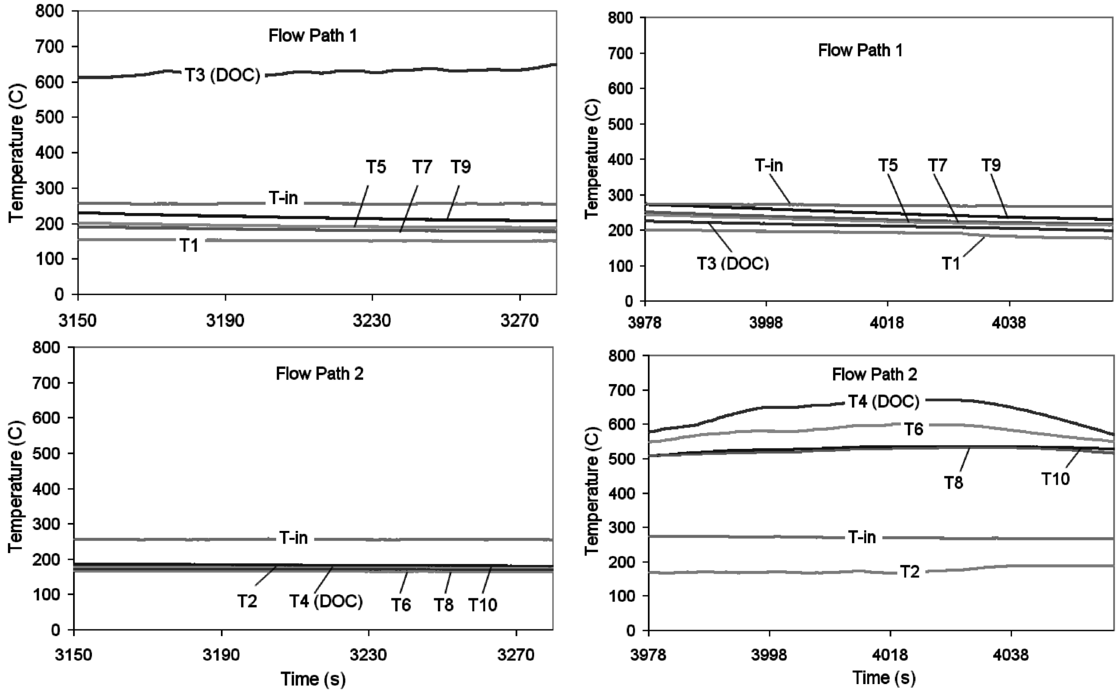


Fig. 15 Temperature histories of two flowpaths in parallel alternating flow.

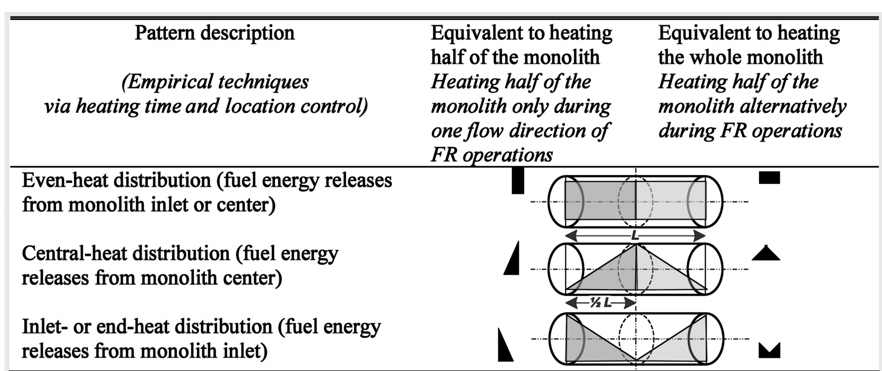


Fig. 16 Symbols of the supplemental energy distribution patterns with normalized total energy.

retention comparison, selected testing results are displayed in the following discussion.

1. Flow Reversal

Figure 13 shows the measured temperature histories during the DPF substrate cooling processes. When the engine is shifted from high to low loads, the exhaust temperature T_g drops quickly from over 600 to ~140°C. Notably, in FR operations, it takes ~400 s for the substrate center temperature T_3 to drop 150°C, whereas in NFR operations, it takes 200 s to have the same temperature drop. FR operations are proved to have an energy-retention effect in this case. More detailed FR control analyses can be found in the previous work [2,12].

2. Parallel Flow

Figure 14 shows the exhaust flow-stagnation testing result in a parallel-flow setup. T_3 and T_4 are temperature sensors at the inlet of each path, and T_1 and T_2 are at the outlet. By shutting off the exhaust flow alternately in mode 1 and mode 2, ~50°C temperature rises were achieved in each flow-stagnated path of the substrate (T_3 and

Table 2 Parallel-flow testing procedures

Test no.	Operations	Inlet port	Flow path 1	Flow path 2
Initial heating	Exhaust flow rate	100%	50%	50%
	External fuel injection	0.8 g/s	Off	Off
	Target	Heat substrate temperature to ~650°C		
1	Exhaust flow rate	100%	10%	90%
	External fuel injection	Off	0.014 g/s	Off
	Target	Keep path 1 substrate temperature ~650°C		
2	Exhaust flow rate	100%	90%	10%
	External fuel injection	Off	Off	0.02 g/s
	Target	Keep path 2 substrate temperature ~650°C		

T_4), which partially agrees with the simulation results. By carefully scheduling the mode switching and external fueling rate, the substrate temperature was maintained at ∼600°C despite engine running conditions.

Additional results in alternating-flow restriction tests are shown in Fig. 15. The idealized monolith patterns are shown in Fig. 16. The testing procedure is listed in Table 2. The temperature sensor positions are shown in Fig. 2. Initially, the substrate temperature was raised to ∼600°C by injecting supplemental diesel fuel (0.08 g/s). During the cooling process, exhaust flow rate restriction techniques were applied alternately in each flowpath as 10 and 90% of the total flow rate. To maintain the high temperature, additional supplemental fuel (0.01 g/s) was injected toward the low flow rate path of the substrate. By applying the appropriate external fueling rate and flow-switching schedule, a desired temperature history was attained fairly irrespective of engine operating conditions. Such active flow control techniques are very important in continuous DPF regeneration and lean NOx trap operations that require relatively strict temperature controls.

V. Conclusions

The active flow control aftertreatment work was conducted from analytical and empirical approaches. The following conclusions can be drawn:

1) Active flow control strategies such as flow reversal and alternating parallel flow are effective to attain the targeted substrate temperatures in the aftertreatment devices with the aid of an external supplemental fuel.

2) In a flow-reversal operation, applying the external supplemental energy to the central region of the substrate is effective to raise the substrate temperature and to maintain the high temperature for a desired duration, at minimum external fuel consumption.

3) In alternating parallel-flow operations, applying the external supplemental energy can raise and maintain the targeted substrate temperature in a more energy-efficient way via flow restriction and flow stagnation.

Acknowledgments

The research is sponsored by the Canada Research Chair program, Natural Sciences and Engineering Research Council of Canada (NSERC), Canada Foundation for Innovation (CFI), Ontario Innovation Trust (OIT), AUTO21, EcoCing of Calgary, the Clean Diesel Research Consortium, and the University of Windsor. Corning, Umicore, Emission Control Systems, and Emitec provided materials and/or products for this research.

References

[1] Zheng, M., and Reader, G. T., "Energy-Efficiency Analyses of Active-Flow Aftertreatment Systems for Lean-Burn Internal Combustion Engines," *Energy Conversion and Management*, Vol. 45, Nos. 15–16, 2004, pp. 2473–2493.
doi:10.1016/j.enconman.2003.11.006

[2] Zheng, M., Reader, G. T., Wang, D., Zuo, J., Wang, M., Mirosh, E. A., Van der Lee, A., and Liu, B., "A Thermal Analysis of Active-Flow Control on Diesel Engine Aftertreatment," SAE 2004 Transactions, SP-1900, *Journal of Fuels and Lubricants*, 2004, pp. 1951–1963; also Society of Automotive Engineers, Paper 2004-01-3020, 2004.

[3] Reader, G. T., Banerjee, M., Wang, M., and Zheng, M., "Energy Efficiency Analysis of Active-Flow Operations in Diesel Engine Aftertreatment," Society of Automotive Engineers, Paper 2006-01-3286.

[4] Konstandopoulos, A. G., Kostoglou, M., Skaperdas, E., Papaioannou, E., Zarvalis, D., and Kladopoulou, E., "Fundamental Studies of Diesel Particulate Filters: Transient Loading, Regeneration and Aging," *2004 SAE Diesel Engine Technology Collection* [CD-ROM], SP-1497, Society of Automotive Engineers, Warrendale, PA, 2004; also Society of Automotive Engineers, Paper 2000-01-1016, 2000.

[5] Schenk, C., Laroo, C., Olsen, B., and Fisher, L., "Four-Flow Path High-Efficiency NOx and PM Exhaust Emission Control System for Heavy-Duty On-Highway Diesel Engines," Society of Automotive Engineers, Paper 2003-01-2305, 2003.

[6] Konstandopoulos, A. G., and Kostoglou, M., "Reciprocating Flow Regeneration of Soot Filters," *Combustion and Flame*, Vol. 121, No. 3, 2000, pp. 488–500.
doi:10.1016/S0010-2180(99)00156-X

[7] Haynes, T. N., Georgakis, C., and Caram, H. S., "The Design of Reverse Flow Reactors for Catalytic Combustion Systems," *Chemical Engineering Science*, Vol. 50, No. 3, Feb. 1995, pp. 401–416.
doi:10.1016/0009-2509(94)00243-K

[8] Hevia1, M.A.G., Fissore, D., Ordóñez, S., Diez, F. V., Barresi, A. A., and Baldi, G., "Comparison of the Performance of a Reverse Flow Reactor and Networks of Non-Stationary Catalytic Reactors for Catalytic Combustion of Methane in Lean Mixtures," *AIChE 2006 Annual Meeting: Engineering Sciences and Fundamentals, Catalysis and Reaction Engineering Division* [CD-ROM], American Inst. of Chemical Engineers, New York, and Omnipress, Madison, WI, 13–16 Nov. 2006, Paper 557f.

[9] Zheng, M., Asad, U., Reader, G. T., and Ting, D. S-K., "A Preliminary Thermal Response Analysis of Exhaust Pipe Plenums for Diesel Aftertreatment Improvement," Society of Automotive Engineers, Paper 2006-01-3310, 2006.

[10] Kiencke, U., and Nielsen, L., *Automotive Control Systems*, Springer–Verlag, Berlin, 2000, Chap. 3.

[11] Eastwood, P., *Critical Topics in Exhaust Gas Aftertreatment*, Engineering Design Series, Research Studies Press, Hertfordshire, England, U.K., 2000, Chaps. 3, 5, 7.

[12] Wang, D., Wang, M., Reader, G. T., and Zheng, M., "A Numerical Study on Uncontrolled Regeneration Processes in Diesel Particulate Filters," *Proceedings of the ASME Internal Combustion Engine Division 2004 Fall Technical Conference* [CD-ROM], American Society of Mechanical Engineers, New York, 24–27 Oct. 2004; also American Society of Mechanical Engineers, Paper ICEF2004-860, 2004.

[13] Zheng, M., Reader, G. T., Wang, D., Zuo, J., Kumar, R., Mulenga, M. C., Asad. U., Ting, D. S-K., and Wang, M., "A Thermal Response Analysis on the Transient Performance of Active Diesel Aftertreatment," SAE 2004 Transactions, *Journal of Fuels and Lubricants*, Vol. 114, No. 4, 2005, pp.1804–1816; also Society of Automotive Engineers, Paper 2005-01-3885.

[14] Zheng, M., Wang, D., Reader, G. T., and Wang, M., "Empirical and Theoretical Investigations of Active-Flow Control on Diesel Engine After-Treatment," Society of Automotive Engineers, Paper 2006-01-0465, 2006.

[15] Aneja, R., Bolton, B., Oladipo, A.B., Pavlova-MacKinnon, Z., and Radwan, A., "Advanced Diesel Engine and Aftertreatment Technology Development for Tier 2 Emissions," FreedomCAR & Vehicle Technologies Program, *9th Diesel Engine Emissions Reduction (DEER) Conference*, Session 8, U.S. Dept. of Energy, 2003, p. 22; also available online at http://www1.eere.energy.gov/vehiclesandfuels/resources/proceedings/.

[16] Zheng, M., Mirosh, E., Klopp, W., Ulan, D., Pardell, M., Newman, P., Bunimovich, G., Matros, Y., and Nishimura, A., "Development of a Compact Reverse-Flow Catalytic Converter for Diesel Dual Fuel LEV," *2004 SAE Diesel Engine Technology Collection* [CD-ROM], SP-1476, Society of Automotive Engineers, Warrendale, PA, 2004; also Society of Automotive Engineers, Paper 1999-01-3558, 1999.

A. Gupta
Associate Editor