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# FUEL MIXTURE ACTIVATION TECHNOLOGIES FOR CUSTOMS FACILITY INFRASTRUCTURE (Integrated fuel mixture activation technology by dissolving combustible gas (methane, propane, or a propane–butane gas mixture) in diesel fuel or gasoline prior to its injection into the combustion chamber within the infrastructure of a customs facility)

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## Abstract

This article examines integrated fuel mixture activation technology and the design of a dedicated activation device intended to improve the preparation of fuel mixtures prior to their injection into the combustion chamber. Particular attention is devoted to the engineering principles of complex fuel activation, the optimization of combustion processes, and the enhancement of engine performance without requiring modifications to the combustion chamber or its operating conditions.

The publication analyzes the principal technical advantages of the proposed technology, including external monitoring and regulation of the fuel activation process, increased concentration of dissolved combustible gases within the fuel mixture, improved pressure retention in fuel microdroplets, enhanced air distribution following injection, shortened activation cycles, and the capability of processing multicomponent fuel mixtures containing both organic and inorganic constituents, as well as functional additives. The study further considers the advantages of achieving these improvements without additional external energy sources while maintaining compatibility with existing engine systems.

Special emphasis is placed on the commercial potential of the integrated fuel activation technology. The article discusses opportunities for reducing fuel consumption, increasing the effective octane rating of fuel mixtures, improving engine operating characteristics, lowering equipment manufacturing and installation costs, enabling the utilization of low-calorific fuels and blended fuel compositions, and combining fuel activation, dissolution, and mixing processes within a single technological system.

The publication further examines the integration of the proposed fuel activation technology with advanced combustion concepts, including Homogeneous Charge Compression Ignition (HCCI). Particular attention is devoted to improvements in combustion efficiency, reduction of combustion temperatures and harmful emissions, enhancement of fuel atomization and combustion kinetics, increased heat release performance, support for near-adiabatic combustion conditions, and the implementation of external monitoring and remote control technologies for fuel preparation prior to injection. The study concludes that the proposed integrated activation approach offers significant potential for improving the efficiency, environmental performance, and commercial competitiveness of next-generation internal combustion engine technologies.
**Keywords:** *Supersystem of the infrastructure and ecosystem of the customs workspace and its transition into an advanced smart integrative combined system; Subsystem of the infrastructure and ecosystem of the customs workspace and its transition into an advanced smart integrative combined system; Transformation of complex constituent parts, supersystems, and subsystems of infrastructure; Metallization in a directed electrolyte flow; Emergence of the edge effect; Production of electronic printed circuit boards for modules and control and monitoring units of a smart mobile home; Engineering, technology, and design in the formation of structural systems and infrastructure inherent in smart manufacturing and a smart mobile home and its equivalents*

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## Introduction

An integrated technology for influencing the fuel mixture prior to its injection into the combustion chamber is proposed.

The proposed technology is based exclusively on well-established and repeatedly verified physical principles and laws embodied in a compact integrated engineering design.

The proposed technology and the device implementing it can be applied to existing internal combustion engine systems without any modification of their design or operating principles.

The proposed technology utilizes only well-known and widely used combustible fuel components and their combinations.

The proposed technology also enables the integrated use of both conventional and newly formed fuel components generated during the activation and dissolution processes, which are subsequently mixed with the primary fuel components through the operating characteristics of the proposed activation device.

A universal and flexible technology is proposed, allowing multiple technological configurations to be implemented within a single activation device.

The proposed technology incorporates a control, monitoring, and regulation system based on a minimal number of monitored and controlled process parameters that have a direct relationship with and influence on both the efficiency of the fuel mixture activation process and the efficiency of fuel combustion in achieving the required energy and environmental performance.

## Description of the fuel mixture activation process

The objectives of the fuel mixture activation process are to increase the octane or cetane rating of the fuel mixture supplied to the combustion chamber during each operating cycle; reduce fuel consumption; increase the specific calorific value of the fuel; improve combustion uniformity; increase combustion completeness; reduce the concentration of toxic exhaust gases; maximize the energy released during combustion; reduce vibration and aerodynamic noise generated during combustion; provide reliable remote control of both the combustion process and the activation process prior to fuel injection; and ensure that all monitored and controlled parameters directly influence the combustion performance within the combustion chamber.

The technological sequence of the fuel mixture activation process is as follows.

The primary fuel component, representing the dominant proportion of the fuel mixture, is stored in a hermetically sealed fuel tank equipped with continuously operating sensors measuring viscosity, density, temperature, and fuel level. Signals from these sensors are transmitted to the process control system.

The control system operates a fuel pump with regulated and monitored flow rate and pressure. The pump delivers the liquid fuel component through the fuel pipeline connected to the inlet of the integrated fuel mixture activation device.

Within the first section of the activation device, the fuel stream supplied under pressure is transformed, accelerated through a series of microchannels, and brought to a highly turbulent flow condition.

In the second section of the activation device, a pressurized stream of compressed combustible gas is introduced into the highly turbulent liquid flow. Owing to its high linear velocity, the gas stream creates a localized low-pressure region at the point of entry into the liquid stream. This localized pressure reduction facilitates the penetration of the compressed combustible gas into the liquid fuel, despite the incompressible nature of the liquid phase.

At the interface between the gaseous and liquid media, the localized low-pressure region generates a pseudo-boiling volume that subsequently develops into a foam-like structure. Under the combined pressure of the system, this foam advances toward the combustion chamber. By the end of its travel, the combustible gas becomes completely dissolved within the liquid fuel, and the resulting fuel mixture containing dissolved combustible gas is injected directly into the combustion chamber.

### 1.1.Possible fuel mixture components

1.2. The components of the fuel mixture that undergo mixing and activation within the fuel mixture activation device may be classified into several groups.

1.3. The principal and dominant group of components consists of liquid hydrocarbons, including gasoline, diesel fuel, ethanol, and kerosene.

1.4. An auxiliary group of liquid hydrocarbon components that may also be used in the fuel mixture includes synthetic gasoline, biologically derived hydrocarbons, and liquefied gas.
1.5. An auxiliary group of liquid fuel mixture components consists of inorganic liquids, such as purified water, synthetic water, and synthetic water generated directly within the engine by means of a heat pipe.
1.6. As an alternative inorganic liquid fuel component, water saturated with coal or carbon dust may also be utilized.
1.7. As a gaseous fuel component, compressed combustible gas or aerosols based on mixtures of combustible gases with various hydrocarbons obtained through the integrated filtration of combustible gas prior to its delivery to the compressor may be employed.
1.8. Description of design options for the fuel mixture activation device
1.9. The integrated fuel mixture activation device consists of two principal operating sections.
1.10. The first section, in the direction of fuel mixture flow, is the hydraulic section, followed by the pneumatic section.
1.11. The hydraulic section incorporates a design that includes a system for intensive vortex mixing of the liquid fuel mixture components. This process is accomplished without the use of additional energy sources and utilizes the same structural elements whose primary function is to increase the turbulence level of the flowing medium.
1.12. The pneumatic section is intended to increase the flow velocity of the compressed combustible gas, introduce this gas stream into the turbulent flow of the liquid fuel components, transform the integrated stream of all fuel components into a foam-like structure, and discharge the integrated activated fuel mixture containing dissolved combustible gas into the fuel pipeline.
1.13. The integrated fuel mixture activation device is installed within the fuel pipeline and is provided with a hermetically sealed, high-pressure-resistant housing equipped with fastening elements for connection to the fuel pipeline.
1.14. Advantages of the fuel mixture activation process resulting from the design features and operating characteristics of the activation device.
1.15. The principal advantage of the integrated fuel mixture activation device is that the activation process within both of its primary operating sections is based on the Bernoulli principle.
1.16. The channel through which the fuel mixture components flow is formed by transforming the cylindrical fuel pipeline into an annular flow channel of larger diameter with a relatively small gap between the concentric cylindrical surfaces while maintaining an equivalent total flow cross-sectional area. This configuration creates preliminary conditions for the formation of turbulent flow regions and promotes the accelerated dissolution of combustible gases within liquid hydrocarbons.
1.17. The localized regions in which the critical physical phenomena associated with the Bernoulli effect are generated are arranged sequentially along the direction of fuel mixture flow. As a result, the liquid fuel components are accelerated, vortex turbulence zones are created, and streams of compressed combustible gas or combustible gas mixtures are introduced into these regions at high pressure and velocity.
1.18. The entire process takes place within a hermetically sealed, high-strength housing, making it possible to substantially increase the pressure of the combustible gas. Upon interaction with the incompressible liquid fuel components, the compressed gas forms small, high-pressure gas bubbles within the liquid phase. Because the activation process occurs within a closed volume, the position of these gas bubbles and their distribution relative to the liquid fuel components remain stable throughout the residence time of the fuel mixture within the activation device and the fuel pipeline until its injection into the combustion chamber.

1.19. Consequently, the principal beneficial properties of the integrated activated fuel mixture are generated by the distinctive structural characteristics of the integrated fuel mixture activation device itself.
1.20. Previously tested technologies that preceded the development of the integrated fuel mixture activation technology and their contribution to its performance characteristics.
1.21. The development of the integrated fuel mixture activation technology was preceded by technologies for the aerodynamic capture and handling of objects in various media, including gaseous and liquid environments.
1.22. During the development of aerodynamic gripping technologies, aerodynamic grippers were created that provided approximately a tenfold increase in lifting capacity while maintaining the same geometric dimensions and energy consumption.
1.23. The highly effective methods for generating localized low-pressure zones, together with the engineering tools developed for producing such regions, were substantially modified by the inventors of the earlier technologies and subsequently incorporated into the integrated fuel mixture activation technology.
1.24. Characteristics of the integrated fuel mixture activation technology prior to injection into the combustion chamber
1.25. The originality of the integrated fuel mixture activation technology lies in its use of the Bernoulli principle to intensify all processes associated with the transformation, dissolution, and mixing of the various liquid and gaseous components of the fuel mixture.
1.26. A second aspect of its originality and effectiveness is the sequential, stage-by-stage creation of technological conditions that enable the beneficial effects of the Bernoulli principle to be utilized in achieving the desired output characteristics of the activated fuel mixture.
1.27. A third aspect of the technology's effectiveness lies in the combination of the structural advantages of the activation device with the operational benefits derived from applying the Bernoulli principle throughout the activation process.

### Sequential description of the technological stages of the fuel mixture activation process

The **first technological stage** consists of preparing the dominant liquid hydrocarbon component before it enters the fuel pump. At this stage, the principal parameters of the component, including density, viscosity, temperature, and fuel level within the storage tank, are continuously monitored.

The **second technological stage** consists of comparing the signals received from the sensors with the statistical model stored in the processor. If the measured parameters correspond to the statistical model, the processor issues a command to activate the fuel pump.

The **third technological stage** consists of starting the fuel pump and delivering the liquid fuel into the fuel pipeline. During this stage, the pressure within the fuel pipeline is measured and transmitted to the processor. If the measured pressure corresponds to the specified value, the processor issues a command to activate the compressor. If the pressure deviates from the prescribed value, the operating parameters of the fuel pump are adjusted until the required pressure is achieved, after which the compressor is activated.

The **fourth technological stage** is performed simultaneously with the fifth stage. It consists of activating the compressor and monitoring the pressure of the compressed combustible gas within the gas pipeline. If the pressure reaches the specified value, the processor authorizes continuation of the activation process. If the pressure differs from the prescribed level, the compressor operating parameters are adjusted until the required pressure is achieved. Since all geometric parameters of the gas pipeline remain constant, the gas pressure determines both the flow rate and the velocity of the compressed combustible gas throughout the pneumatic section of the fuel mixture activation device.

The **fifth technological stage**, performed simultaneously with the fourth stage, consists of transforming the liquid fuel stream within the hydraulic section of the activation device and increasing its level of turbulence.

The **sixth technological stage** is an optional stage applied when the fuel mixture contains a second liquid fuel component. During this stage, which is also performed simultaneously with the fifth stage, the second liquid component is drawn into the localized low-pressure zone and intensively mixed with the primary fuel component.

The **seventh technological stage** constitutes the principal stage of the activation process. Its primary objective is to saturate the liquid fuel component with dissolved combustible gas, convert the resulting mixture into a foam-like structure, and subsequently restore the system pressure to its original operating level.

The **eighth technological stage** consists of monitoring the dielectric permittivity of the integrated activated fuel mixture. If the measured dielectric permittivity corresponds to the statistical model, the processor issues a command to inject the activated fuel mixture into the combustion chamber. If the measured value differs from the specified parameter, both the fuel pump pressure and the compressor pressure are adjusted until complete agreement between the measured parameters and the statistical model is achieved, after which the processor authorizes fuel injection.

## Schematic arrangement of the devices and components comprising the fuel system of an automobile or aircraft utilizing the integrated fuel mixture activation technology

The integrated fuel mixture activation device may be incorporated into the fuel system of any automobile, aircraft, or other vehicle equipped with an internal combustion engine.

The essential components of the system include fuel component reservoirs, fuel pipelines, a fuel pump, a compressor, the integrated fuel mixture activation device with a storage vessel for liquefied combustible gas, and a system of sensors and monitoring devices.

An optional subsystem consists of a real-time resonant monitoring system for measuring the dielectric permittivity of the fuel mixture immediately prior to its injection into the combustion chamber.

## Operating procedure of the fuel mixture activation device as applied to the fuel system of an automobile or aircraft engine

### Operating characteristics of the activated fuel mixture prior to its injection into the combustion chamber

The integrated activated fuel mixture produced by the two-stage mixing, turbulence enhancement, and foaming device possesses the following principal characteristics prior to injection into the combustion chamber.

The integrated activated fuel mixture may contain combinations of liquid organic fuel components and combustible gases dissolved within them, mixed in various proportions such that components present at lower concentrations are uniformly distributed throughout the volume of the dominant fuel component.

The integrated activated fuel mixture may also contain combinations of organic and inorganic fuel components mixed in various proportions so that the inorganic components are uniformly distributed throughout the organic phase.

Following completion of the activation cycle, the integrated activated fuel mixture constitutes at least a two-component liquid system in which numerous dissolved combustible gas molecules are uniformly distributed throughout the liquid phase while remaining under the pressure of the fuel pipeline. These dissolved gas molecules retain the kinetic energy imparted by the highly developed turbulent flow generated during the activation process.

## Operating characteristics of the activated fuel mixture after its injection into the combustion chamber

One of the most important characteristics of the integrated activated fuel mixture is its octane rating, which serves as an indicator of resistance to engine knock. For premium gasoline produced by catalytic reforming, this conventional indicator is approximately 86. The anticipated octane rating of activated gasoline containing combustible gas dissolved at a concentration of approximately 10% by the mass of the liquid hydrocarbon is expected to reach approximately 120.

The technical capabilities of the integrated fuel mixture activation device also make it possible to produce gasoline–benzene mixtures, where benzene possesses an octane rating of approximately 113. Such a modification is expected to increase the octane rating of the activated fuel mixture to approximately 125.

The activated fuel mixture exhibits a mass burning rate approximately one order of magnitude greater than that of conventional fuel mixtures. The mass burning rate is defined as the quantity of fuel consumed per unit area of the combustion front per unit time.

The activated fuel mixture also exhibits sufficiently high combustion reaction rates and heat release rates – the quantity of thermal energy released per unit time – to maintain stable combustion even under reduced-temperature operating conditions.

Furthermore, the activated fuel mixture satisfies the conditions required for adiabatic combustion, whereby the combustion reaction is completed before significant heat exchange occurs between the reaction volume and the surrounding environment, thereby minimizing thermal and energy losses.

## Methods for regulating the principal operating characteristics of the activated fuel mixture; capability for remote control and regulation of the fuel mixture activation process; regulated fuel mixture parameters; feedback during monitoring and regulation

The integrated fuel mixture activation technology incorporates two principal technological parameters that determine both the degree of activation and the overall effectiveness of the process.

The first parameter is the pressure within the fuel pipeline generated by the fuel pump. Since the internal diameter of the fuel pipeline remains constant, the pressure within the pipeline determines both the flow velocity and the volumetric flow rate of the liquid fuel. These direct and derived parameters determine the turbulence level of the flowing medium, which, in turn, governs the degree of turbulence generated within the hydraulic section of the integrated fuel mixture activation device, whose geometric parameters remain constant. Consequently, by regulating the pressure within the fuel pipeline, it is possible to control the activation process occurring in the hydraulic section of the device. Pressure signals transmitted to the control processor provide an accurate assessment of the condition of the fuel mixture prior to its injection into the combustion chamber and enable automatic adjustment of the fuel pressure to restore the required operating conditions.

The second parameter is the pressure within the pipeline supplying compressed combustible gas to the pneumatic section of the integrated fuel mixture activation device, where the gas is dissolved within the liquid hydrocarbon fuel.

This parameter is considered the most important because the pressure of the gaseous working medium – primarily methane or propane – determines the flow velocity of the compressed combustible gas. This velocity governs several fundamental factors upon which the effectiveness of the activated fuel mixture depends.

The flow velocity of the compressed combustible gas determines the following principal characteristics of the integrated activated fuel mixture:

- the proportional relationship between the dissolved gaseous phase and the liquid phase of the fuel mixture;
- the uniformity of distribution of the dissolved gaseous phase throughout the volume of the liquid fuel component.

Accordingly, the pressure of the compressed combustible gas supplied to the integrated fuel mixture activation device determines the magnitude and effectiveness of the principal properties and characteristics of the activated fuel mixture. Regulation of this pressure makes it possible to control the principal operating characteristics of the fuel mixture.

Pressure measurements also provide reliable real-time feedback reflecting the condition and properties of the activated fuel mixture throughout the activation process.

## Principal operating parameters of the integrated activated fuel mixture providing advantages over existing fuel preparation technologies

The principal operating parameters of the integrated activated fuel mixture include the concentration of dissolved combustible gas within the fuel mixture and the specific active contact surface area of the fuel mixture following its injection into the combustion chamber.

Prior to injection into the combustion chamber, the condition of the integrated activated fuel mixture is characterized by the following parameters:

- the quantity of dissolved combustible gas per unit volume of the fuel mixture;
- the ratio between the quantity of dissolved combustible gas and its volumetric content within the fuel mixture;
- the specific density of a unit volume of the activated fuel mixture;
- the specific contact surface area per unit volume of the activated fuel mixture.

Where several fuel components are combined during the integrated activation process, the modified octane rating or cetane rating of the resulting fuel mixture becomes an additional important indicator of its performance.

## Description of the injection process of the integrated activated fuel mixture into the combustion chamber and the advantages achieved during injection

The injection process of the integrated activated fuel mixture possesses characteristics that are not typical of conventional fuel mixtures.

Within the integrated activated fuel mixture, the internal pressure may reach considerable values. While the mixture remains inside the activation device and within the fuel pipeline upstream of the combustion chamber, this condition remains stable.

Following injection into the combustion chamber, the volume occupied by the injected fuel charge expands. The excess pressure within the spray plume fragments the fuel stream into microdroplets, while the dissolved combustible gas, possessing a lower boiling point than the liquid fuel components, simultaneously ruptures the liquid envelope surrounding the droplets. This envelope is dispersed into a finely atomized three-dimensional structure exhibiting a relatively uniform distribution throughout the combustion chamber prior to ignition.

This volumetric distribution of the activated fuel mixture provides the following advantages:

- high combustion velocity;
- a high degree of combustion completeness;
- a uniform combustion front;
- high heat release within a short period of time;
- a short overall combustion cycle;
- high specific energy output resulting from fuel combustion;
- low levels of micro-vibration and micro-shock during combustion;
- reduced concentrations of toxic combustion products in the exhaust gases;
- lower combustion temperatures, resulting in reduced emissions of toxic exhaust gases.

## Predicted and calculated characteristics of the combustion process of the integrated activated fuel mixture

The principal performance characteristics used to evaluate the combustion process of the integrated activated fuel mixture include the combustion rate, flame propagation velocity, combustion completeness, specific calorific value during combustion, and the concentration of toxic substances within the combustion products.

Additional performance characteristics include the mass burning rate, linear burning rate, combustion-front surface area corresponding to a unit volume of the fuel mixture, combustion reaction rate, and heat release power.

Auxiliary performance characteristics include the turbulent flow parameters of the fuel mixture during its injection into the combustion chamber. These turbulence-induced pulsations intensify heat transfer and mass transfer within the flame, distort and fragment the combustion front, expand the combustion reaction zone, and thereby produce a substantial acceleration of the combustion process.

The turbulent flame propagation velocity of the integrated activated fuel mixture is expected to exceed the corresponding values observed in conventional fuel mixtures by several tens of times.

## Technical and commercial advantages of applying integrated fuel mixture activation prior to injection into the combustion chamber

The application of integrated fuel mixture activation in combination with the design of the integrated fuel mixture activation device provides, in comparison with existing fuel preparation systems and technologies intended for preparing the fuel mixture prior to its injection into the combustion chamber, a number of technical advantages that directly determine significant commercial benefits.

The principal technical advantages include:

- the ability to perform fuel mixture activation prior to injection into the combustion chamber without any modification to the combustion chamber design or its operating conditions;
- the ability to achieve a high level of kinetic energy during the activation process without the use of additional external energy sources;
- the ability to perform continuous monitoring and regulation of the activation process without accessing the combustion chamber, using only standard external monitoring instruments and standard external control methods for adjusting the required process parameters;
- the ability to increase the specific concentration of dissolved combustible gas within the fuel mixture;
- the ability to increase and maintain high pressure within the microdroplets of the fuel mixture during the injection process;
- the ability to achieve highly uniform air distribution throughout the fuel mixture after injection;
- the ability to substantially reduce the duration of the activation cycle;
- the ability to process multicomponent fuel mixtures within a single activation device;
- the ability to activate fuel mixtures containing both organic and inorganic components within the same activation device;
- the ability to activate fuel mixtures containing alloying or functional additives within a single integrated activation system.

The principal commercial advantages of the integrated fuel mixture activation technology include:

- reduced fuel consumption during the combustion process;
- increased octane or cetane rating of the fuel mixture;
- improved operational characteristics of internal combustion engines;
- significant reduction in the manufacturing cost of the integrated fuel mixture activation device;
- low installation costs for integrating the activation device into vehicles;
- the capability of utilizing low-calorific fuels and blended fuel compositions in internal combustion engines;
- the capability of performing fuel activation, dissolution, and mixing of fuel components simultaneously within a single integrated device.

The combination of the integrated fuel mixture activation technology with advanced internal combustion engine cycle modification technologies currently under development, including **Homogeneous Charge Compression Ignition (HCCI)** technology, is expected to provide the following additional advantages:

- increased concentration of air or other oxidizing agents within the fuel mixture;
- reduced combustion temperature within the combustion chamber;
- reduced or completely eliminated concentrations of toxic exhaust gases;
- increased atomization fineness of the fuel spray during injection into the combustion chamber;
- an approximately 100- to 1,000-fold increase in the active surface area of the fuel mixture following injection into the combustion chamber;
- increased combustion completeness of the fuel mixture;
- increased heat release power;

- establishment of conditions favorable for adiabatic combustion;
- increased mass burning rate;
- increased linear flame propagation velocity;
- increased combustion reaction rate;
- reduced vibration and detonation during the engine operating cycle;
- complete remote monitoring of fuel mixture parameters outside the combustion chamber;
- remote control of the fuel preparation process prior to injection into the combustion chamber, based on accurate real-time measurements of the actual concentration of dissolved combustible gas within the fuel mixture immediately before injection.

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