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(54) **System amd method for controlling a fan insufflating ait into a protected space, especially in fire ventilation for the protection of escape routes**

(57) The object of the invention is a system for controlling a fan insufflating air into a protected space, especially in fire ventilation for the protection of escape routes, comprising a controller equipped with a processor with a high computational power and a memory, designed and configured to control the said fan by setting frequency U of the inverter controlling the motor of said fan and connected to this inverter, and in addition connected to a pressure sensor for measuring pressure difference P between the protected space and a reference pressure, characterised in that the said controller is configured and programmed to perform the following steps:
a) registering, in the memory of the controller, parameters of the fan, determined in time;
b) registering, in the memory of the controller, parameters of the protected space, variable in time;
c) determining the value of parameter *a(k)* at current moment k as a function of *a(k)=P(k)/U2(k);*
d) determining the value of control *U(k+1)* at a subsequent moment of time *k+1,* by solving the task of non-linear optimisation by means of an iterative method, the feasible point of the iterative method being assumed as *Ustart(k+1)=Sqrt(P(k)/a(k));*
e) setting the so determined value of control *U(k+1)* as a frequency of the inverter controlling the fan motor.

The object of the invention is also a method for controlling a fan insufflating air into a protected space, especially in fire ventilation for the protection of escape routes.

Model of a controlled process with a division into static and dynamic parts (Wiener- Hammerstein model)

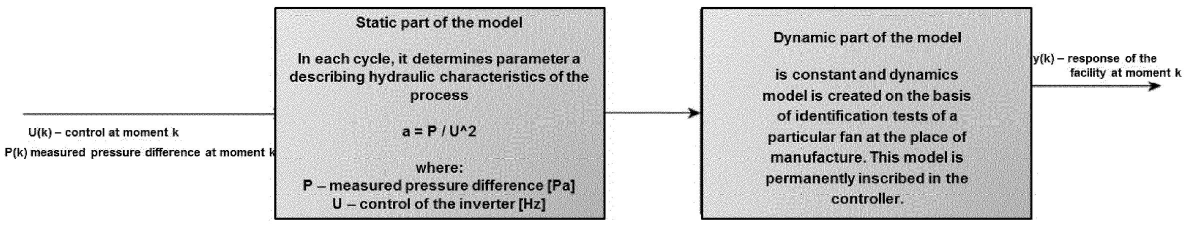

Fig. 2

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Description

[0001] The invention relates to an active system and method for controlling a fan insufflating air into a protected space, especially in fire ventilation for the protection of escape routes, by differentiating pressures.

[0002] In buildings where people are present (residential or public utility buildings), conditions for safe evacuation of people during a fire have to be ensured, and appropriate conditions for rescue teams after the evacuation have to be created. The concept of safe evacuation should be understood as maintenance of vertical and horizontal escape routes free from smoke and organised reception of smoke from this space of the building. This is an issue of crucial importance to safety of users of the facility because, as analyses of effects of fires clearly indicate, smoke (mixture of gaseous combustion products with air) is the primary threat to their lives. Smoke accompanies all fires, limiting visibility in escape routes, and poses a very serious risk of intoxication to people who remain in the facility. A particularly serious threat is posed by toxic combustion products, such as: carbon monoxide, gaseous hydrochloric acid HCl, hydrocyanic acid or sulphur compounds, which constitute a high share of fire gases. For example, carbon monoxide is poisonous because when in contact with blood, it binds to the blood pigment - haemoglobin, with which it has 200-240 times higher affinity than oxygen. This is a durable, coordinate binding of carbon monoxide with iron atoms of haemoglobin, the binding, as a consequence, preventing the natural reaction of haemoglobin with oxygen. Impact of carbon monoxide on people is multiplied due to the phenomenon of hyperventilation, i.e. an increased respiration rate, which causes rapid accumulation of carbon monoxide in the organism. Figuratively speaking, two breaths in a smoky space cause loss of consciousness and, consequently, threaten with death. The above discussed threats to life are of particular importance in multistorey buildings where evacuation of people is carried out through corridors, elevators and stairways. With relatively low heights of stories, large amounts of smoke, generated during a fire, in a short time fill the entire cubature of the room on the storey and in the absence of appropriate technical safeguards they can rapidly threaten not only the evacuation of the directly threatened storey, but also of other users of the building.

[0003] The ventilation system in multi-storey buildings has to provide two (steady) stable states. The first: all the doors leading to the protected space (e.g. a stairway) are closed: overpressure of a fixed value (selected from the range of 30 Pa to 80 Pa, most often 50 Pa) has to be ensured. The second: at least one door is opened, e.g. from the fire involved corridor to the stairway, the fan insufflating air into the protected space needs to increase its flow rate so as to ensure air speed in the door opening at a specified level (e.g. 1 m/s or 2 m/s). To ensure an acceptable level of protection, transitional period between these two states should not last longer than three seconds.

[0004] Fire ventilation systems currently in use are divided into passive and active ones. An attempt to solve the problem of fire ventilation involves passive, mechanical systems for removing smoke and for maintaining the escape routes free from smoke. In the lower part of the stairway, a fan inflating clean air with a constant flow rate is placed so as to meet the criterion of flow in the open door, and in the upper part, a smoke release vent with a weight selected so as it opens, for example, at an overpressure of 50 Pa, is placed. The active systems are built as automatic control systems with the use of PID controllers. A sensor for sensing pressure in the protected space is connected to the PID controller. Based on the measurement, the controller determines the required power of the fan and, in the form of a voltage signal or through a serial transmission link, transmits it to an inverter (frequency converter) which directly controls the fan motor. This application relates to an active system.

[0005] In the prior art, there is a number of passive solutions which relate to the control of fan operation based on the measurement of pressure difference between the protected/insulated space and a reference pressure, and which maintain a constant pressure difference. Exemplary solutions are disclosed in the following publications: KR 100317243 B1, DE 19937532 A1, DE 10241625 A1, CN 203024345 U, JP 2007/024469 A. However, solutions of this type have an important disadvantage. Wind blowing along the plane of the vent (perpendicularly to its axis) causes an increase in dynamic pressure and a decrease in static pressure. This increase in static pressure combined with water hammer (at the time of the door closure) leads to a complete opening of the vent and to a permanent blockage of it in an open position.

[0006] In the prior art, there are solutions which relate to the control of fan operation (not only in the fire ventilation system) for obtaining an expected pressure difference, on the basis of indications of temperature values inside and outside the building. For example, publications JP 2005/207674 A, US 2012/0164930 A1 and JPH 07139775 A relate to air conditioning devices, and PL 389314 A1 refers to a fire ventilation system.

[0007] In publications EP 2511617 A1, EP 1990584 A1, EP 0915300 A2 and WO 2007/127897 A2, solutions disclosing a method for controlling air flow by controlling the fan operation are shown. In particular, publication EP 0915300 A2 discloses a method for controlling pressure, according to which, based on an established mathematical model, predicted settings are calculated. Forecasts are adjusted on an ongoing basis. A similar solution was described in publication WO 2007/127897 A2. The invention relates to an adaptive feedback algorithm (e.g. PID) which is used in a controller of fluid flow. A disadvantage of these solutions is that active systems equipped with a PID controller can operate properly only in facilities with a constant and large leakage. In real facilities, changes in leakage may be sudden (e.g. breaking of window pane) or smooth (e.g. operation of a door closer on a storey not covered by fire). Large leakage means that in the closed state of the door, the fan has a large flow rate, i.e. there is a small change in leakage between the two operational states, and the facility can be approximated by a linear model, which allows selection of appropriate settings for the PID controller. If the leakage is small, and this is the case in the newly constructed buildings, the range of variability in leakage is large, the system is highly non-linear and the PID controller becomes unstable: in the system, there are strong oscillations, i.e. the fan cyclically accelerates to the maximum flow rate, then decelerates to zero, etc. The only solution is to suppress the controller, i.e. to select the settings so that it reacts very slowly, but then it is not possible to achieve the transition period of less than three seconds. The use of PID control is therefore not possible for two reasons: firstly, a high non-linearity of the controlled facility, secondly, the facility is non-stationary: its characteristics change over time. The most important parameters which change over time include: leakage, air density and wind strength and direction. Change in leakage causes a complete change of air distribution in the building, which is also affected by the strength and direction of the wind: air can be forced into the interior, for example, through ventilation holes. An important parameter is air density (which depends on atmospheric pressure, temperature and humidity) because Reynolds number depends on density, and change in this number affects the effective flow rate of the fan. Therefore, the use of advanced control algorithms, e.g. predictive ones, seems to be the natural way. Unfortunately, all control algorithms require a mathematical model of the facility. The facility is non-stationary so this model has to be created on an ongoing basis and very quickly because control variables are rapidly changing, according to the control theory at least 20 times per second. The facility is highly non-linear: e.g. function describing the flow rate of the fan, according the frequency of the inverter, is non-linear and depends on the variable parameters of air (Reynolds number). Further, the non-linear model requires a solution of non-linear optimisation task with restrictions (of control, i.e. the range of possible frequencies of the inverter is restricted to the range of 0 - 50[Hz], or 0 - 60[Hz]). Such a task has not any solutions in the general case, and iterative methods require very high computational power of the processor and have an indefinite time to reach the solution, thus the cannot be used in real time for very dynamic (rapidly changing) processes. This is confirmed by literature on the subject: predictive algorithms with solution of optimisation task are currently used mainly in the chemical industry for slowly changing processes.

[0008] The solution to these problems is the invention being applied.

[0009] A key element of the invention is a pressure controller together with a sensor (measurement of the pressure difference between the protected space and a reference pressure, e.g. atmospheric pressure). The controller is equipped with a processor with a high computational efficiency, equipped with floating-point arithmetic (high precision of calculations). The present inventors have surprisingly noted that the model of controlled process can be divided into two components: a static part describing the steady state and a dynamic part describing unsteady states. The essence of the invention consists in the fact that the static part of the model describes, in its entirety, hydraulic properties of the facility (leakage, current efficiency of the fan), whereas the dynamic part describes characteristics of the fan itself: motor dynamics and aerodynamic characteristics of the fan blades. The dynamic part is constant and the (non-linear) dynamics model is created on the basis of identification tests of a particular fan at the place of manufacture. This non-linear dynamics model is permanently inscribed in the controller. On the other hand, the static part of the process model is identified on an ongoing basis in each cycle of intervention of the controller (minimum cycle is 25[ms]): the controller brings the process to the steady state (a fraction of a second being enough) and based on the measurement of pressure difference and on knowledge of current frequency of the inverter, it calculates parameter *a* which describes hydraulic characteristics of the process, according to the formula: *P=a.U^2,* where P represents measured pressure difference, U represents control, i.e. frequency at which the inverter controls the fan motor. Determination of current values P and U allows calculation of current value of parameter *a=P/U^2.* This process performed with a period of controller intervention provides current non-linear model to the rest of the algorithm, the task of the said rest being to find an optimal trajectory of the control, i.e. control values for subsequent moments of time: current moment k, and subsequent ones *k+1, k+2, k+3,*... Normally, it is performed by solving the task of non-linear optimisation with restrictions. Unfortunately, there is not any general solution to such a task, iterative methods are used, the said methods not guaranteeing to achieve a global solution within the required short time. Another element of the invention is a method for quickly solving the task of non-linear optimisation, used in the invention. The present inventors have surprisingly noted that optimal trajectory differs by not more than 5% (most often) to 10% (in extreme cases) from the trajectory in the steady state, which at current moment can be calculated from the formula: *u(k)=u(k+1)=u(k+2)=···=sqrt(P/a).* The so determined point in the control space is in close proximity to the optimum solution (global minimum of the task of non-linear optimisation). Therefore, the feasible point of the task of non-linear optimisation is a predicted control trajectory for the steady state, determined as a result of identification of parameter *a*. This guarantees the convergence of the optimisation task and achieving the solution within the required short time.

[0010] The object of the invention is a system for controlling a fan insufflating air into a protected space, especially in fire ventilation for the protection of escape routes, comprising a controller equipped with a processor with a high computational power and a memory, designed and configured to control the said fan by setting frequency U of the inverter controlling the motor of this fan and connected to this inverter, and in addition connected to a pressure sensor for measuring pressure difference P between the protected space and a reference pressure (reference pressure may be atmospheric pressure or pressure from the room in which a fire can potentially start), characterised in that the said controller is configured and programmed to perform the following steps:

a) registering, in the memory of the controller, parameters of the fan, determined in time, including at least: minimum and maximum control of the inverter [Hz], calibration of current path for controlling the rotational speed of the inverter, determination of operation dynamics of the fan (acceleration time of the fan, deceleration time of the fan);

b) registering, in the memory of the controller, parameters of the protected space, variable in time, comprising at least value *P(k)* read from the pressure sensor, value *U(k)* read from the inverter, inflow of air into the protected space and leakage of air from the protected space, at current moment k;

c) determining the value of parameter *a(k)* at current moment *k* as a function of *a(k)=p(k)/U2(k);*

d) determining the value of control *U(k+1)* at a subsequent moment of time *k+1,* by solving the task of non-linear optimisation by means of an iterative method, the feasible point of the iterative method being assumed as *Ustart(k+1)=Sqrt(P(k)/a(k));*

e) setting the so determined value of control *U(k+1)* as a frequency of the inverter controlling the fan motor.

[0011] The object of the invention is also a method for controlling a fan insufflating air into a protected space, especially in fire ventilation for the protection of escape routes, consisting in that in a system comprising a controller equipped with a processor with a high computational power and a memory, designed and configured to control the said fan by setting frequency *U* of the inverter controlling the motor of this fan and connected to this inverter, and in addition connected to a pressure sensor for measuring pressure difference P between the protected space and a reference pressure, the following steps are performed:

a) in the memory of the controller, parameters of the fan, determined in time, are registered, the said parameters including at least minimum and maximum control of the inverter [Hz], calibration of current path for controlling the rotational speed of the inverter, determination of dynamics of the fan operation (acceleration time of the fan, deceleration time of the fan);

b) in the memory of the controller, parameters of the protected space, variable in time, are registered, the said parameters including at least value *P(k)* read from the pressure sensor, value *U(k)* read from the inverter, inflow of air into the protected space and leakage of air from the protected space, at current moment *k;*

c) the value of parameter *a(k)* at current moment k is determined as a function of *a(k)=P(k)/U2(k);*

d) the value of control *U(k+1)* at a subsequent moment of time *k+1* is determined by solving the task of non-linear optimisation by means of an iterative method, the feasible point of the iterative method being assumed as *Ustart(k+1)=Sqrt(P(k)/a(k));*

e) the controller sets the so determined value of control *U(k+1)* as a frequency of the inverter controlling the fan motor.

Preferred Embodiment of the Invention

[0012] Now, the invention will be presented in greater detail in a preferred embodiment, with reference to the accompanying drawings in which:

Fig. 1 (prior art) shows a known active control system with the use of PID controller;

fig. 2 shows a model of a controlled process with a division into static part A and dynamic part B (Wiener-Hammerstein model);

fig. 3 shows an exemplary graph of the control with an indication of static part A and dynamic part B;

fig. 4 shows a solution according to the invention used in a vertical escape route (stairway in a facility - shopping mall), and

fig. 5 shows an example of a method for controlling fan according to the invention in a real facility - shopping mall.

[0013] In the drawings, the following designations were used: 1- pressure sensor, 2 - aeration unit, 3 - inlet of air flow into a stairway 5 from supply ducts, 4 - system of ventilation (supply) ducts, 5 - stairway; 6 - utility rooms.

[0014] Fig. 2 shows a model of a controlled process with a division into static part A and dynamic part B (Wiener-Hammerstein model), where the input parameter is *U(k)* - control at moment k and *P(k)* - pressure difference measured at moment *k.* Static part A of the model, in each cycle, determines parameter *a* describing hydraulic characteristics of the process, the said parameter being determined from the following equation:

$$a = P/U^2$$

where:

P - represents measured pressure difference [Pa]
U - represents control of the inverter [Hz]

[0015] Dynamic part B of the model is constant and dynamics model is created on the basis of identification tests of a particular fan at the place of manufacture. This model is permanently inscribed in the controller. The output parameter is *y(k)* - constituting a response of the facility at moment *k.*

[0016] In a preferred embodiment, a fire protection system successfully used in a facility, being a shopping mall, is presented. The facility is illustrated schematically in Fig. 4. The system was used to provide protection of vertical escape route in a four-storey stairway 5 with a very large cubature and tightness. The facility comprises the following elements:

- A point for measuring pressure by means of a pressure sensor pmacF - 1. The pressure sensor 1 measures pressure difference relative to a reference pressure, i.e. atmospheric pressure. Location of the pressure sensor 1 in Fig. 4 is exemplary. The pressure sensor 1 is mounted in a place where the air flow entering the stairway from an inlet 3 does not affect directly the point at which the sensor 1 is located. Optionally, the pressure sensor 1 is mounted in other places of the stairway 5.

- An aeration unit 2 consisting of:

    o MAC-FC controller - it constitutes the "heart" of the entire system. In the controller, program containing an algorithm and supporting communication with other elements of the system: the pressure sensor 1, the inverter;

    o Danfoss FC102 inverter for motors with power up to 10KW, which is controlled from MAC-FC controller through a current signal. In addition, the controller monitors operational state of the inverter through a serial transmission port;

    o A 3-phase asynchronous motor with a power of 9.6 KW;

    o A battery power system for MAC-FC controller;

    o A fuse and relay block.

- An inlet of air flow to the stairway 5 from supply ducts 3 directly connected to the aeration unit 2.

- A system of ventilation (supply) ducts 4 which convey air to the protected area;

- The stairway 5 constituting a vertical escape route from all stories of the building. In accordance with operation of the system according to the invention, the stairway 5 has to be free from smoke. Optionally, the escape route in this case is constituted by a corridor, which is a horizontal escape route. The stairway 5 used as a vertical escape route is connected to technical corridors in the shopping mall.

- Utility rooms 6 in which a fire can start. In these rooms, there are people who, in the event of fire, evacuate through the stairway 5 from the burning facility.

[0017] To aerate the stairway 5, in the system according to the invention, the following elements were used:

- MAC-FC controller

- A pressure sensor with a measuring range of 0 to 250 Pa

- Danfoss FC102 inverter

- An 9.6KW AC 3-phase asynchronous motor

[0018] Fig. 5, shows an actual graph of inverter control *U* as a function of time (vertical axis on the right, [Hz]) in the stairway 5 with a presented response of the algorithm to opening and closing the door. A graph of pressure measured by the sensor 1 as a function of time (vertical axis on the left , [Pa]) is also shown. Values of control U achieved by the inverter vary in the range of 0[Hz] to 50[Hz] (control range of the inverter).

[0019] In fig. 5:

- I, II - represents the steady state in the facility (static part A which describes it) - where the algorithm in each cycle with a period of 50[ms] determines static part A of the facility. In the static state, criterion of ensuring a constant overpressure (from 30 to 80[Pa]) has to be met. In the presented case, an overpressure relative to the reference pressure with a value of 50[Pa] is maintained. The control of the fan in this state is 11[Hz];

- III - moment of opening the door (dynamic part B), where an immediate response to the decrease in pressure takes place. In the dynamic state, criterion of ensuring an appropriate flow on the open door (at least 1[m/s]) has to be met. In this state, the control of the fan is 50[Hz] (maximum control that can be set on a given fan);

- IV - moment of closing the door (dynamic part B), where a sudden increase in pressure takes place as a result of closing the door. At this point, a transition to the steady state takes place and the control of the fan changes from 50[Hz] to 11[Hz];

- V - moment of pressure stabilisation after closing the door (about 2[s]) and a transition to the steady state of the facility (static part A). In the static state, like before opening the door, i.e. in the steady state I, II, the fan is controlled with a value of 11[Hz].

[0020] Simultaneously, in fig. 3, static parts A and dynamic parts B of the control process are shown.

Claims

1. A system for controlling a fan insufflating air into a protected space, especially in fire ventilation for the protection of escape routes, comprising a controller equipped with a processor with a high computational power and a memory, designed and configured to control the said fan by setting frequency *U* of the inverter controlling the motor of said fan and connected to this inverter, and in addition connected to a pressure sensor for measuring pressure difference P between the protected space and a reference pressure, **characterised in that** the said controller is configured and programmed to perform the following steps:

a) registering, in the memory of the controller, parameters of the fan, determined in time, comprising at least: minimum and maximum control of the inverter [Hz], calibration of current path for controlling the rotational speed of the inverter, determination of operation dynamics of the fan, especially acceleration time of the fan, deceleration time of the fan;
b) registering, in the memory of the controller, parameters of the protected space, variable in time, comprising at least value *P(k)* read from the pressure sensor, value *U(k)* read from the inverter, inflow of air into the protected space and leakage of air from the protected space, at current moment *k;*
c) determining the value of parameter *a(k)* at current moment *k* as a function of $a(k)=P(k)/U^2(k)$;
d) determining the value of control *U(k+1)* at a subsequent moment of time *k+1,* by solving the task of non-linear optimisation by means of an iterative method, the feasible point of the iterative method being assumed as $U_{start}(k+1)=Sqrt(P(k)/a(k))$;
e) setting the so determined value of control *U(k+1)* as a frequency of the inverter controlling the fan motor.

2. A method for controlling a fan insufflating air into a protected space, especially in fire ventilation for the protection of escape routes, consisting in that in a system comprising a controller equipped with a processor with a high computational power and a memory, designed and configured to control the said fan by setting frequency U of the inverter controlling the motor of said fan and connected to this inverter, and in addition connected to a pressure sensor for measuring pressure difference P between the protected space and a reference pressure, the following steps are performed:

a) in the memory of the controller, parameters of the fan, determined in time, are registered, the said parameters comprising at least minimum and maximum control of the inverter [Hz], calibration of current path for controlling the rotational speed of the inverter, determination of operation dynamics of the fan, especially acceleration time of the fan, deceleration time of the fan;
b) in the memory of the controller, parameters of the protected space, variable in time, are registered, the said parameters comprising at least value *P(k)* read from the pressure sensor, value *U(k)* read from the inverter, inflow of air into the protected space and leakage of air from the protected space, at current moment *k;*
c) the value of parameter *a(k)* at current moment *k* is determined as a function of $a(k)=P(k)/U^2(k)$;
d) the value of control *U(k+1)* at a subsequent moment of time *k+1* is determined by solving the task of non-linear optimisation by means of an iterative method, the feasible point of the iterative method being assumed as $U_{start}(k+1)=Sqrt(P(k)/a(k))$;
e) the controller sets the so determined value of control *U(k+1)* as a frequency of the inverter controlling the fan motor.

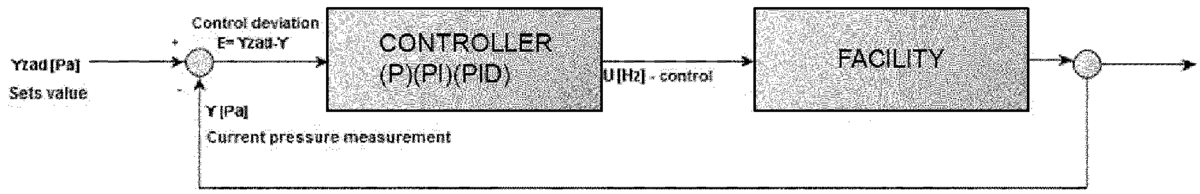

Fig. 1 (prior art)

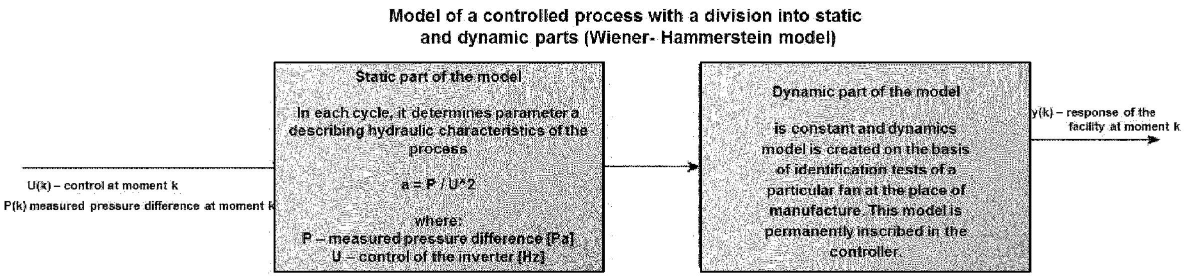
Model of a controlled process with a division into static
and dynamic parts (Wiener- Hammerstein model)
Static part of the model
In each cycle, it determines parameter a describing hydraulic characteristics of the process
a = P / U^2
where:
P – measured pressure difference [Pa]
U – control of the inverter [Hz]
Dynamic part of the model
is constant and dynamics model is created on the basis of identification tests of a particular fan at the place of manufacture. This model is permanently inscribed in the controller.
U(k) – control at moment k
P(k) measured pressure difference at moment k
y(k) – response of the facility at moment k

Fig. 2

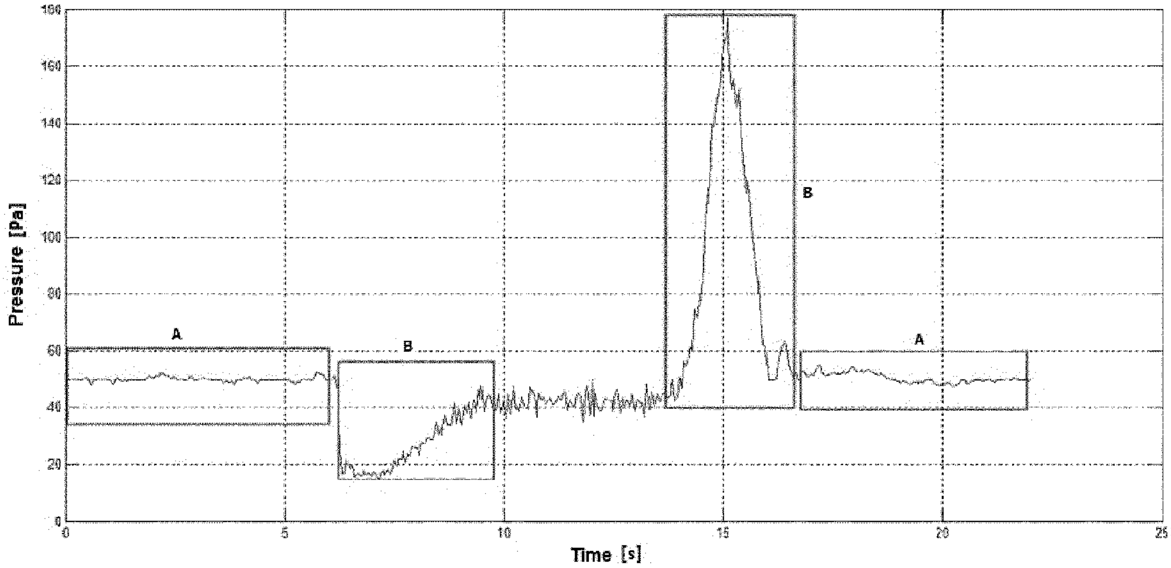
Pressure [Pa]
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Fig. 3

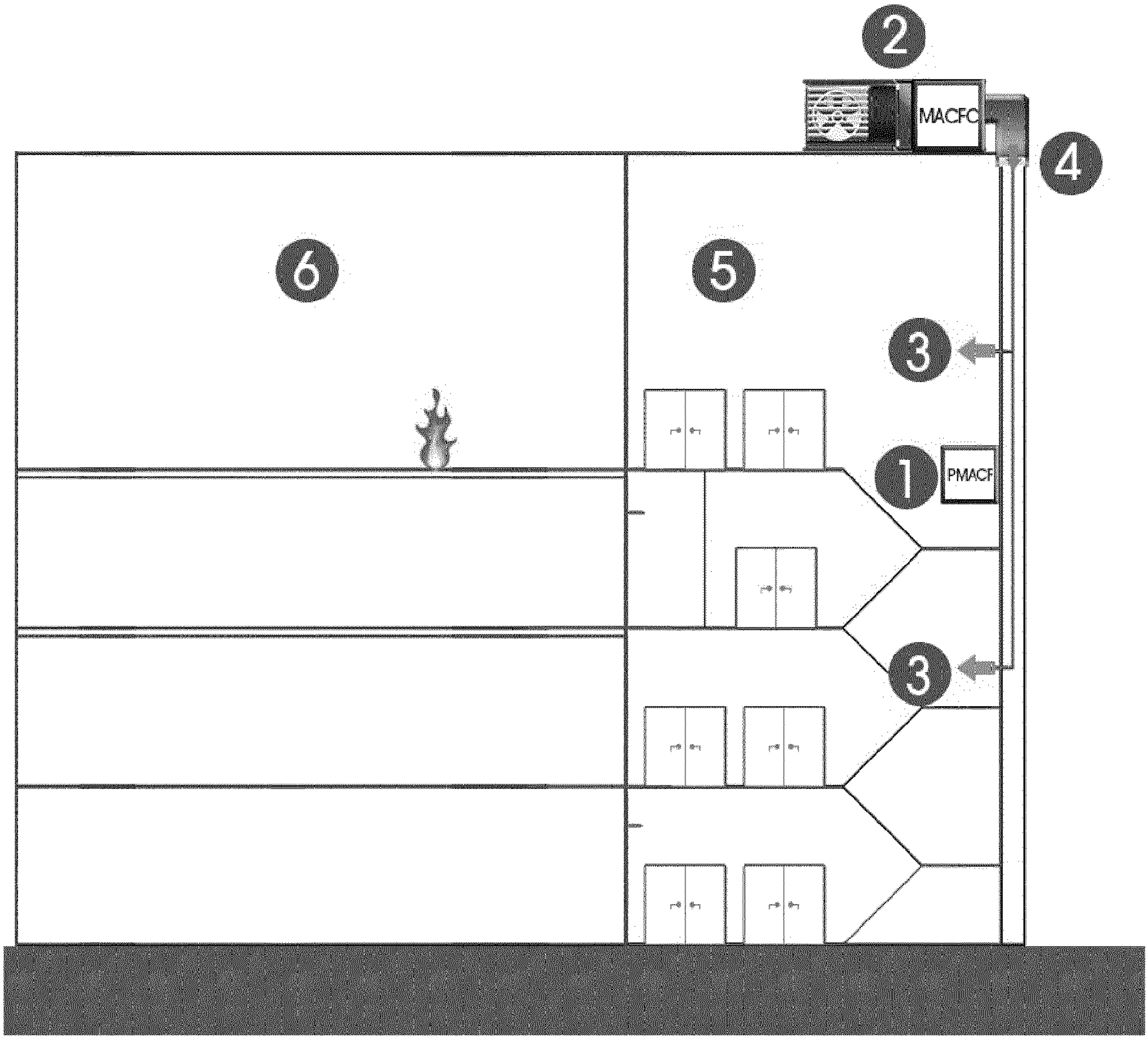

Fig. 4

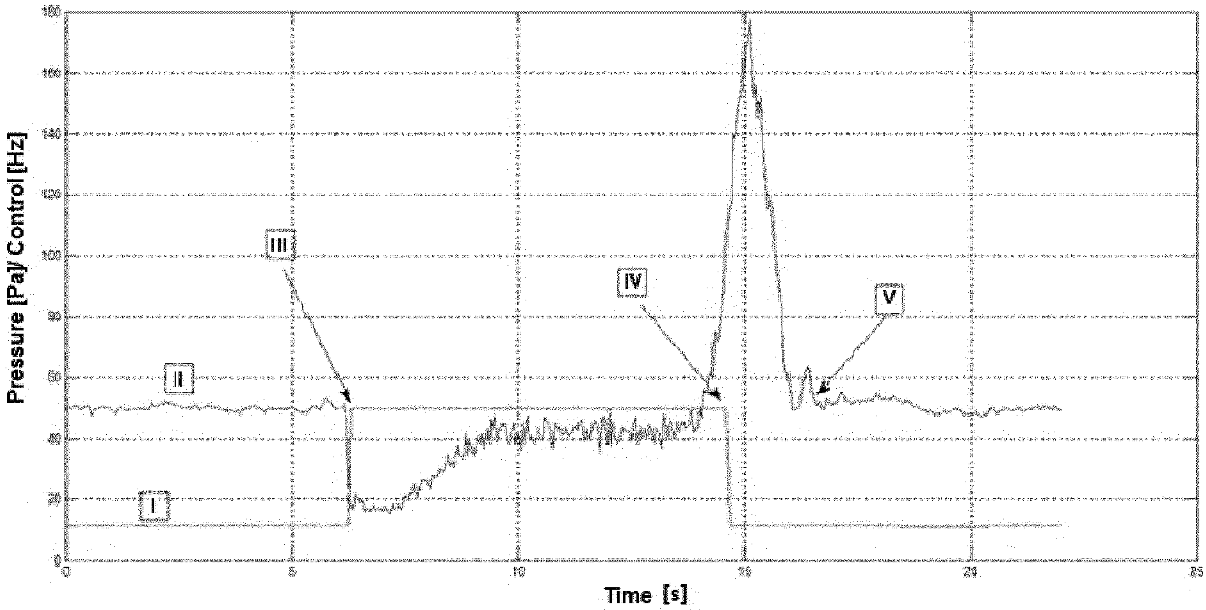

Fig. 5

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EUROPEAN SEARCH REPORT

Application Number
EP 14 46 1509

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
A	CA 2 405 858 A1 (BERGMAN GEORGE [CA]) 1 April 2004 (2004-04-01) * the whole document * -----	1,2	INV. F24F11/00
A	EP 2 345 485 A2 (FIRE ENGINEERING ASSOCIATES LTD [GB]; INTERACTIVE SPECIAL PROJECTS LTD) 20 July 2011 (2011-07-20) * paragraph [0049] - paragraph [0052] * -----	1,2	
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TECHNICAL FIELDS SEARCHED (IPC)

F24F

1

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
Munich	29 July 2014	Vuc, Arianda

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
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EPO FORM 1503 03.82 (P04C01)

ANNEX TO THE EUROPEAN SEARCH REPORT ON EUROPEAN PATENT APPLICATION NO. EP 14 46 1509

This annex lists the patent family members relating to the patent documents cited in the above-mentioned European search report. The members are as contained in the European Patent Office EDP file on
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29-07-2014

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EPO FORM P0459

For more details about this annex : see Official Journal of the European Patent Office, No. 12/82

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