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Antisurge Systems-State of the Art

Filip Grapow

Institute of Turbomachinery, Faculty of Mechanical Engineering,
Lodz University of Technology, Lodz, Poland

E-mail address: filip.grapow@p.lodz.pl

ABSTRACT

Industry today can't exist without compressors. Very often they are most important part of installation and profits of enterprise depends on them. Every failure of this machine results in stoppage of production and therefore enormous loses. One of the biggest threat to stable operation of compressors is flow instability called surge. It occurs in conditions of low mass flow rate and appears as an oscillations of pressure and mass flow and it's capable of destroying machine in just few seconds. To prevent from this dangerous phenomenon antisurge systems are used. In this paper division of antisurge systems and literature study of current knowledge and technologies are presented. Examples of different types of antisurge systems and future trends are discussed. This paper summarize today's state of knowledge about methods of prevention from surge.

***Keywords*:** Surge, antisurge system, compressors, flow instabilities

1. INTRODUCTION

Nowadays compressors are inseparable part of our lives but many people don't realize about it. We can find them in things we use every day like air-conditioning or vacuum cleaner but the most important role of this machines is in industry. Very often compressor is heart of installation so every failure of this machine results in stoppage of production and therefore enormous loses for enterprise. That's why it is so important to provide their stable and undistorted work. Reasons of this failure can be many but one of the most dangerous is phenomenon called surge.

Surge is global and essentially one dimensional flow instability which occurs when mass flow rate is lower than critical. This critical value is marked as so called "surge line". Also temperature, pressure and composition of gas can affect stability of compressor. During surge annulus-averaged mass flow is unsteady but circumferentially uniform [de Jager 1995]. It appears as pressure and mass flow low frequency limit cycle oscillations which in extreme conditions can lead to reverse mass flow. This causes enormous stress levels, thermal loads and is capable of destroying compressor in just few seconds [Meuleman, Willems, et al. 1998]. In jet engines surge can lead even to suction of flame from combustor [Day, Freeman 1993]. Process of this oscillations superimposed on compressor and system performance curves is presented on Figure 1. In this case reverse flow is visible and big amplitude of pressure oscillations. To prevent from this instability or to suppress its harmful effects wide variety of different anti-surge systems are used. Nowadays every compressor which is working on important installations have anti-surge system to provide safe working conditions to compressor and hence constant incomes for company.

In this paper division and description of different types of antisurge systems are described and examples of each type is presented. Analysis of both, articles and patents were made. Approach to predict future trend in antisurge systems development has been done.

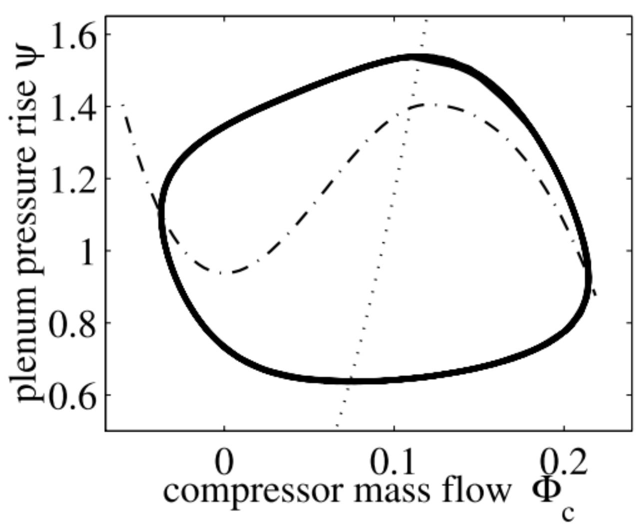

Fig. 1. Typical surge process [Willems 2000]

2. DIVISION OF ANTISURGE SYSTEMS

Antisurge systems protect compressor form harmful effects of surge instability. First distinction between different types of antisurge systems is because of operating environments.

Three primary operating environments are [Brun, Nored, et al. 2008]:

1. Start-up- during start-up of compressor or gas turbine conditions of small mass flow rates occurs. In gas turbine this process take long time to heat up whole machine so for all this time antisurge system has to be working.

2. Normal Process Control- during normal operation antisurge system can't limit operational range significantly. The less it limits the better system is. In this environment antisurge system has to be able to distinguish between normal process changes, start-up and beginning of surge.
3. Shutdown-when suddenly surge appears in compressor emergency shutdown should happen to prevent compressor from destruction. There are two types of compressor shutdown:
   - Controlled shutdown- during controlled shutdown parameters are gradually decreased until full stop. During this situation antisurge system works almost like during Normal Process Control.
   - Emergency Shutdown-during immediate stoppage of compressor exists high risk of surge. Rotational speed is decreased to 80% rpm in 1-1,5 seconds after trip out and there is need to lower discharge pressure to prevent form surge [Boyce, Bohannan, et al. 1983].

Second distinction is because of application of compressor. Different working conditions of compressor demand special behavior of antisurge system. These applications are [Brun, Nored, et al. 2008]:

1. Pipelines- in this application some oscillations of pressure can occur, but surge onset I often due to reduction of mass flow which is governed by the pipeline. Also temperature is changing but seasonally so it is not rapid change. Composition of gas is constant.
2. Re-injection- in chemistry some reactions happened only in particular pressure and by mixing fluids. In this application compressor injects back gas to reactor where reaction happens. All parameters influencing surge are varying. Pressure and temperature can change over time and composition also is changing because of different sources of fluids are injected to reaction.
3. Storage and withdraw-when storage is being filled the pressure and the beginning is low, but when it starts to being full the pressure needed to push gas inside is much bigger. The opposite situation happen when magazine is discharged. Mass flow can vary but not always and the composition of gas is constant. Example of this application is Compressed Air Energy Storage (CAES).
4. Gas Gathering- when gas is gathering it's temperature, pressure and composition depends on source and the preparation of this gas before compressor. By preparation dehydration, separation and filtration are meant.
5. High pressure- in this application disturbances of pressure, temperature and composition happens rarely but the range of these parameter is wide due to variety of different installations. In this applications very high pressures occurs and example can be Liquid Natural Gas Plant.

Last and the most important division is because of point on compressor map at which antisurge system start working or which affects. This division is pointed below [Botros, Henderson 1994] and presented in Figure 2. Control line is just line created by surge margin.

This distinction is described and analyzed in this paper.

1. Prevention
2. Passive control (extending surge limit)
3. Active control
4.

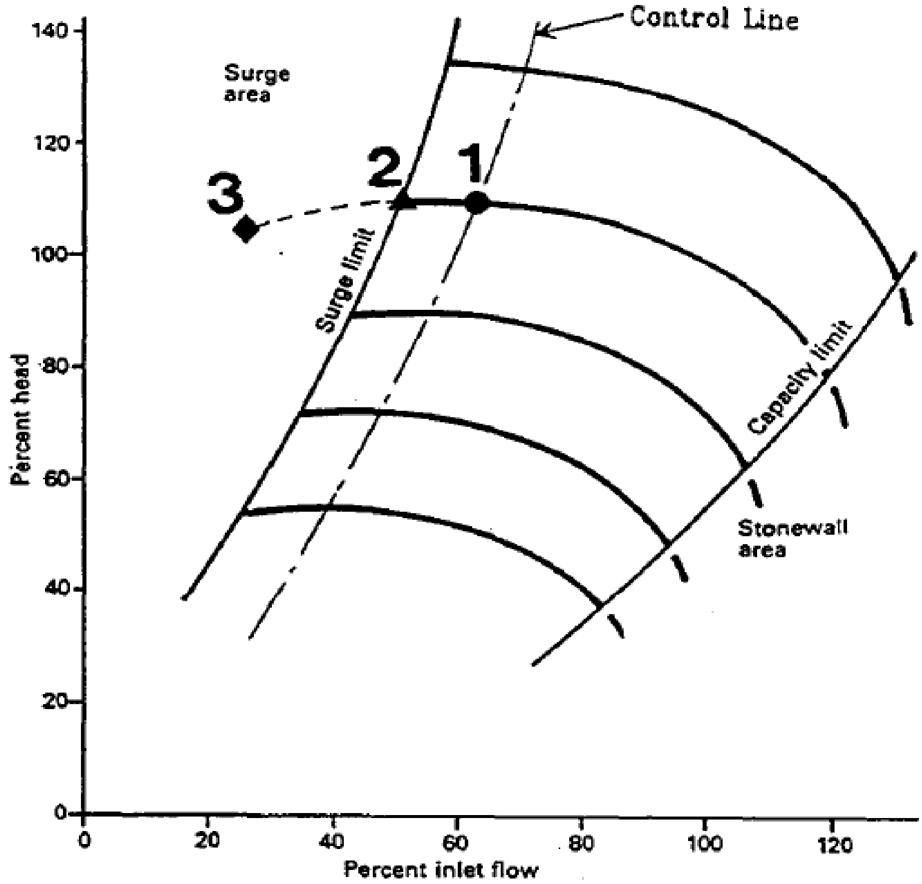

Fig. 2. Typical centrifugal compressor performance map showing surge limit and control line [Botros, Henderson 1994]

3. PREVENTION

First type of antisurge system is prevention. It is based on preventing compressor from surge just by not allowing it to begin. It is connected with preventing form crossing surge line.

This type can be divided on two types:

1. Surge margin
2. Early detection

System based on surge margin is simplest and the least efficient of all types. Compressor controller just do not let to cross predefined operational point. This point is different for all compressor speeds and this points connected create control line which is visible in the Figure 2.

Surge margin narrows the operation range of compressor and very often prevents machine from working at highest possible efficiency. The smaller this margin is the better for operating range and thus the machine, but it cannot be too narrow. Antisurge system has to have time to act and if this margin is too narrow this time can be not enough and surge would occur. The most common used surge margin is 10% of surge limit, but it is not good choice at all cases.

Width of this margin depends on [Mirsky, Jacobson, et al. 2013]:

- Accuracy of surge limit designation. Inaccuracy has to be compensated by larger surge margin,
- Surge limit ability to change. In controler surge limit is constant but in reality it can change,
- Compressor performance curve. Steep curves do not need very wide surge margins,
- Uncertanity of measurments,
- Antisurge system and compression system inertia. Antisurge system has to have time to act and compress ion system can disturbance can escalete even despite antisurge actions.
- Atisurge system objective. In some cases mild surge is acceptable and in others it has to be avoided .

When control line is reached system has to react in somehow to prevent from crosing it. The most common actuator used to prevent from surge is recycle valve. Opening recycle valve causes turn back part of gas from discharge of compressor to suction side artifficialy enlarging mass flow. Recycle valve is most commonly used actuator in all types of antisurge systems. Scheme of example installaion is presented on Figure 3.

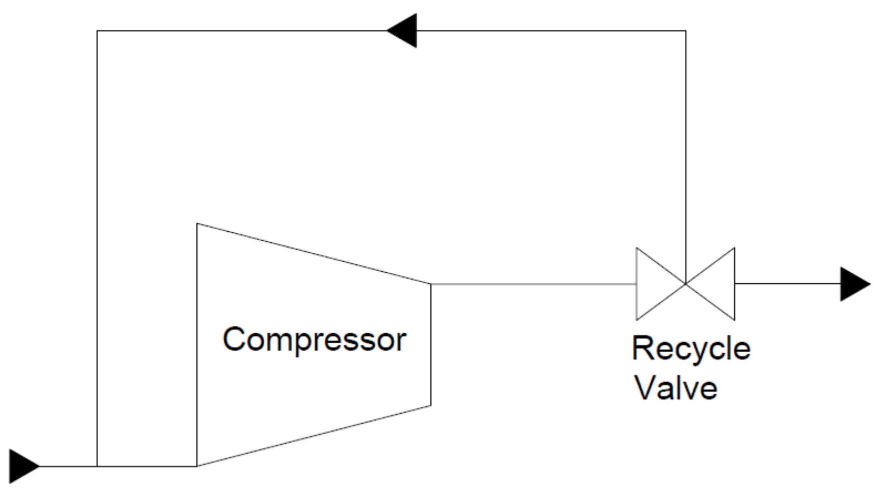

Fig. 3. Scheme of antisurge system with recycle valve

Typical control line and antisurge systems are based on compressor performance curve defined by mass flow and pressure rise. To identify what is current operation point of compressor mass flow and difference between pressure at suction and discharge side are measured. Development of this system was very popular but at 80's and 90's and that's why most of articles and patents considering this type are relatively old: [White 1972; Kolnsberg 1979; Boyce, Bohannan, et al. 1983; Staroselsky, Mirsky, et al. 1990; Hohlweg, Condrac 1986; Blotenberg 1990; Bellinger, Clayton 1980; Enterline, Kaya 1985]. There are not many new articles concerning conventional antisurge systems, only [Amin, Mahmood-ul-hasan 2015], but new patents are submitted for example [Rosinski, Belanger, et al. 2013]

But there are other systems based on different curves and different parameters measured. This division is pointed below [Gravdahl, Egeland 2011]:

1. Conventional anti-surge control- it is typical antisurge system which is described earlier in this paper.
2. Flow/Rotational speed (Q/N) technique- in this method fan law characteristics are used. This operation allow reduction of many performance curves to reduce them to one curve by normalizing mass flow and polytropic head with respect to rotational speed. In this case surge line is just one point. Mass flow and rotational speed is measured and when value of Q/N is too low, recycle valve opens. Examples of this kind of system can be found in [Di Febo, Di Febo 2014; Swearingen, Agahi 1991; Lawless, Stickel 1990].
3. Microprocessor and PLC based controller- This method is more complicated and take into consideration more factors than just mass flow and pressure. Additional measurements are needed like temperature or suction temperature to identify more accurately current operation point. Examples of this kind of system can be found in [Joshi, Barnes, et al. 2016; Hobbs 1989; Ramos 1987; C. Gao, Gu, et al. 2008; Xiaogang, Pinglu, et al. 2013].
4. Control without flow measurements- flow measurements are very often noisy and inaccurate so are the source of significant uncertainty. So as in Q/N technique again fan law characteristic is used but this time polytropic head to rotational speed squared (H/N^2) but requirement to use this method is steep performance curve. Difference between polytropic head at two points has to be big enough to distinguish these two points from each other.

System based on early detection do not set surge margin but is based on measurements which helps to detect surge onset just before it starts. This solution almost does not limits operational range of compressor but needs more complicated measuring system. What is more all components of early detection antisurge system need to be quick because any latency can lead to surge and thus compressor failure.

There are three main types of measurements which can be used to detect surge incipient [Botros, Henderson 1994]:

1. Vibration measurements- the less effective method because of problematic distinction between rise of vibration due to surge and the other sources of vibrations. To strict program can interrupt start-up of machine and too mild program can miss surge onset and risk machine condition. Examples of this kind of system can be found in [Johnsen 2013]

2. Temperature measurements- flow oscillations and reverse flows during surge changes heat distribution in compressor. Temperature is rising in some places like space located within the impeller chamber of the compressor but out of fluid flow or compressor inlet. By monitoring temperature in this locations it is possible to detect surge onset but it has to be compared with other values like rotational speed or discharge pressure. Examples of this kind of system can be found in [Sisson, Petrizzi 1998; Gaston 1986; Preti, Ripy 1979]
3. Pressure and it derivatives measurements- most popular method with numerous technologies and patents. In this type of antisurge system location of measurements, number of probes and manipulation of the pressure signals with respect to time can vary. Examples of this kind of system can be found in numerous patents and articles. For example in [Stalker, Blutinger 1976; Galeotti, Pelagotti, et al. 2016; Krukoski 1989; Glennon, Sarphie, et al. 1979; Callahan, Mazzawy, et al. 1985; Clark, Perrone 1987; Lowe, Hagerman 1986]

4. PASSIVE SYSTEMS

Point 2 on Figure 2 represents passive control which delays surge onset. Previously described method based on surge margin significantly limits operation range of compressor, early detection slightly affects operating range and method described in this chapter not only do not limits operation range but also extends it. Passive system is not based on measurement and its influence on compressor is not function of any measured parameter. One of possible realization of this antisurge system is by changing construction of compressor. There are several factors which can delay surge onset:

1. Blade geometry
   a. Number of blades [Gottschalk 1972]
   b. Higher angle at impeller exit [Cumpsty 1989]
   c. Thickening of blades suction side [Flynn, Weber 1979]
2. Diffuser geometry
   a. Reducing exit width [Ludtke 1983]
   b. Decreasing number of vanes [Japikse 1980]
   c. Different shape of inlet [Whitfield, Wallace, et al. 1976]
   d. Vane inlet geometry [Bammert, Jansen, et al. 1983]
   e. Different ratio of diffuser inlet and rotor outlet [Pampreen 1972; Dean 1974]
3. Casing modifications [Ding, Wang, et al. 2013]
   a. Grooves at different locations (Fig. 4) [Jansen, Carter, et al. 1980]
   b. Chambers at different locations [Wiggins, Waltz 1977; Waterman 1992]
4. Volute geometry [Stiefel 1972; Lipski 1979]

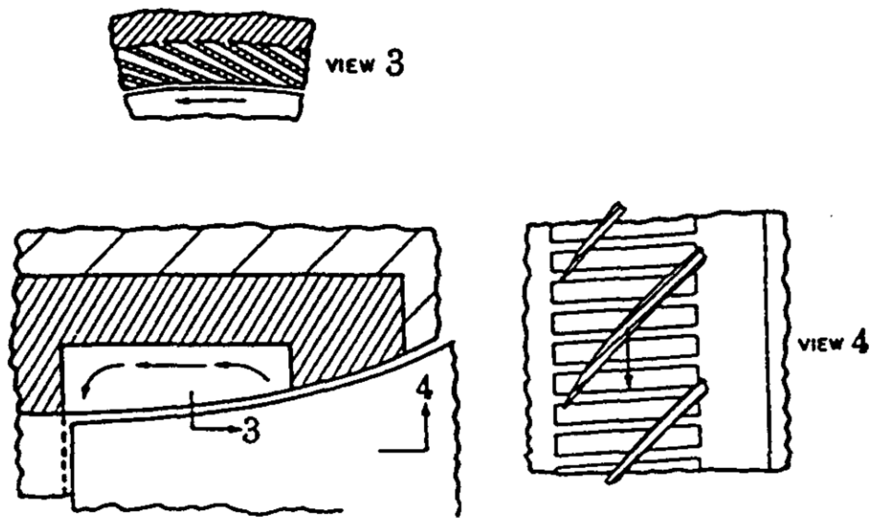

Fig. 4. Inclined axial grooves at impeller inlet for surge suppression [Jansen, Carter, et al. 1980]

Another realization of passive antisurge system is by using additional components which are not controlled by any measurement. There are not many of this type of antisurge systems but those based on generating proper prewhirl at inlet of compressor gave satisfactory results. It can be achieved by using Inlet Guide Vanes (IGV) [Whitfield, Wallace, et al. 1976; Amann, Nordenson, et al. 1975] or reinjection from discharge side [Kyrtatos, Watson, et al. 1980; Hirano, Uchida, et al. 2012; Skoch 2004]. IGV has significant drawback which was pressure loss. Another interesting passive system is based on adding resistance element placed close to discharge of compressor [Pfannebegker, Singhania 1977]. It changes performance curve of combined compressor/resistance so it become more stable.

This type of antisurge system cannot be only system in compression system. It only extends surge limit but do not prevents from surge. It have to be used with prevention or active control system. It is used but as a part of designing machine. Constructor has to choose optimal point between surge suppression and efficiency.

5. ACTIVE CONTROL

Active control is most complicated of all methods but also most often investigated by researches all around the world. This type of antisurge system suppresses surge and allows compressor to work in unstable conditions.

Scheme of typical active control antisurge system is presented on figure 5. It consist of three elements. Sensor measures controlled parameter and transmit it to controller. Controller basing on difference between actual condition and desired condition send signal to actuator which by control action affects compression system and suppress surge.

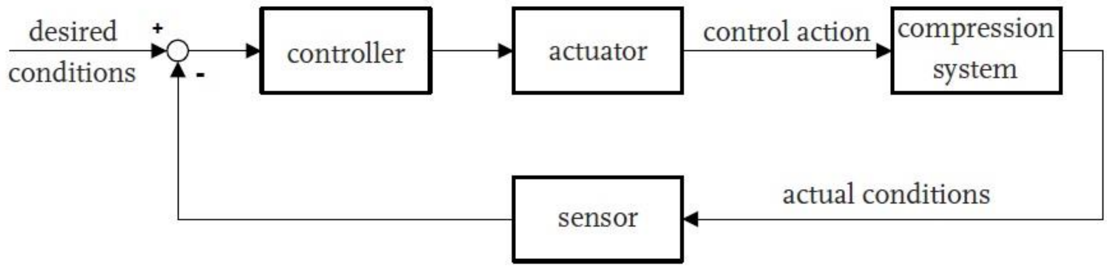

Fig. 5. Scheme of active control antisugre system [van Helvoirt 2007]

Like it was said before, recycle valve is most commonly used actuator in antisurge systems so also in active systems. Sometimes instead of recycle valve, bleed valve is used but the influence on compression system is the same. In prevention method this valve is opened when operational point reached surge margin. In active system this valve is not only open or close but its position is dynamically regulated by controller and its adjusting to current state of compression system. This regulation is close-looped so valve is almost constantly moving. This actuator was one of the first analyzed active systems and was studied by [Chowdhury, Eveker, et al. 1995; Badmus, Chowdhury, et al. 1996; Jungowski, Weiss, et al. 1994; Pinsley, Guenette, et al. 1991; Hagino, Uda, et al. 2003; Gravdahl, Egeland 1999; Gravdahl, Egeland 2011; Gravdahl, Egeland 1997; Willems, de Jager 1998a]. Also many recent researches considers this type of antisurge system [Backi, Gravdahl, et al. 2016; A. Cortinovis, Pareschi, et al. 2012; Andrea Cortinovis, Ferreau, et al. 2014; A. Cortinovis, Ferreau, et al. 2015; Daniarta, Wardana, et al. 2016; Grapow 2015]

Other actuators also has been investigated but not so widely as recycle valve. In table 1 summary of the other actuators has been presented. Most of this actuators focuses on damping pressure oscillations in compression system by releasing some of gas or like movable wall by increasing its volume. Another improves stability similarly to systems based on extending operating range like inlet guide vanes or air injectors. It can be said that active systems are using very similar actuators as previous methods but in this systems, actuators are regulated real-time by controller. Models used to control this process are very often complicated and dedicated to one machine. Those basing on proportional feedback are the simplest but nowadays Model Predictive Control (MPC) [A. Cortinovis, Pareschi, et al. 2012; Andrea Cortinovis, Ferreau, et al. 2014; A. Cortinovis, Ferreau, et al. 2015] is getting more and more popular. This regulation is based on different mathematical models of surge which are still being enhanced by researchers. Most popular are model based on Greitzer model [Greitzer 1976]. Also more complicated approaches to control has been analized like Fuzzy Logic [Chen, Jiang 2010], Neural Network [Boushaki, Chetate, et al. 2014] or Least Square Support Vector Machine (LS-SVM) [S. Gao, Qian, et al. 2016; Wang, Shao, et al. 2010].

In table 1 next to actuators, sensors are enlisted. Pressure is most widely used because of relatively easy measurements and because surge firstly reveals as a pressure oscillations. Mass flow is also used but as it was said before, mass flow measurements is very noisy and uncertain. Also velocity measurement using hot wires are possible to properly control actuator.

Table 1. Actuators and sensors of active control
[Willems, De Jager 1999; Willems, de Jager 1998b]

Actuator	Sensor
Recycle or bleed valve	Plenum pressure
Injection in compressor duct [Weigl, Paduano, et al. 1997]	Plenum temperature
Variable plenum volume [Gysling, Dugundji, et al. 1991]	Inlet mass flow
Variable inlet geometry	Inlet pressure
Fast inlet guide vanes [Haynes, Hendricks, et al. 1993]	Diffuser pressure
Air injectors [Behnken, D'Andrea, et al. 1995; Yang, Li, et al. 2017]	Hot wires
Auxiliary compressor stage	
Plenum mass injection	
Inlet duct bleed	
Heat coil	
Plenum loudspeaker [Williams, Huang 1989]	
Close-coupled valve	

Active control is complex method which needs individual approach to every compression system. Creating model for compressor, tests and implementation of such a system is very time-consuming anf expensive . Nevertheless it is still mos twanted kind of system due to its efficiency and reliability.

6. CONCLUSIONS

In this paper state of the art of compressor antisurge system has been presented and discussed. Three different types of antisurge systems were described and current patents and articles has been enlisted.

Prevention by setting surge margin is the simplest and less effective than other systems. It limits operation range and sometimes does not allow compressor to operate at highest efficiency or highest pressure rise. This method is widely used in industry because it is cheap, simple and reliable but nowadays researches rarely investigate this method but there is still few new patents. Early detection limits operation range less than surge margin but can be risky due to requirement of very quick control system and actuators. This system detects surge incipient basing on different measurements but moment of surge onset is different for every machine so this system has to be individual. It is still developed by researches but not very often and new patents also are submitted.

Passive system is also used but as an element during designing compressor. Factors enlisted in chapter 4 are being considered and optimal point between surge suppression and efficiency is found. More popular are design modification than additional elements. Improvements in compressor design which helps to extend operating range are rather discovered during researches on efficiency improvements than in separate researches.

Last described antisurge system which was active control is most desired kind of antisurge systems because of its universality, efficiency and reliability. It allows compressor to operate in surge region without harming compressor. It is possible because of real-time control of different kinds of actuators which are controlled basing on variety of measurements. Both, actuators and control methods are widely investigated so it is not only mechanical issue but also automatic. Many papers has been published in recent years and most of them concerning systems based on recycle/bleed valve.

Active system is the best of all described systems but it is most complex and expensive type of antisurge system. It can be used as stand-alone system but best effects and reliability can be achieved only by combining even all three systems described before.

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