Automatic Controls 1400-1985

Controls History

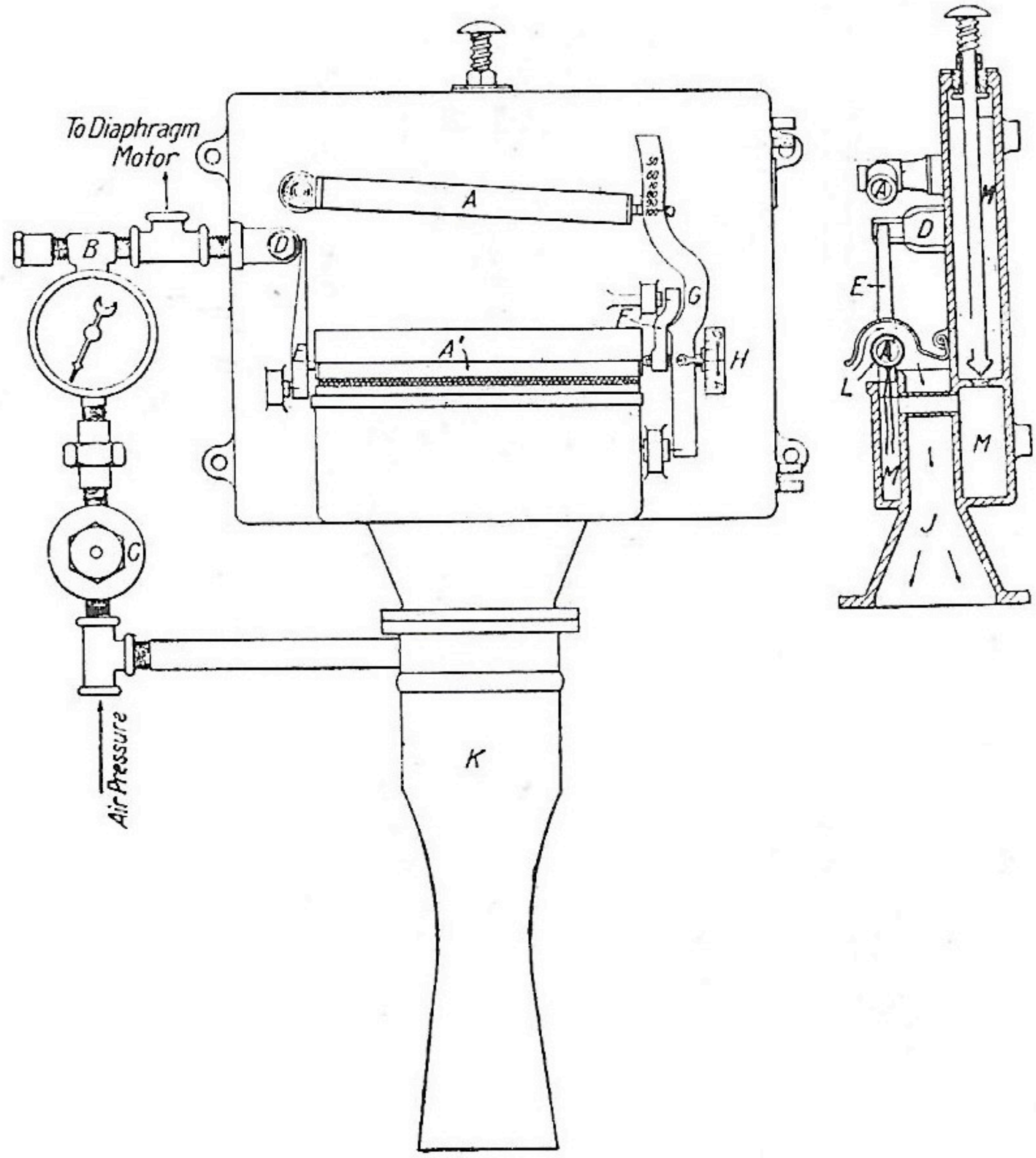


Fig. 11.10. Carrier differential hygrostat (1911).

From BUILDING SERVICES ENGINEERING
A REVIEW OF ITS DEVELOPMENT

N S Billington & B M Roberts, 1982

Chapter 11

AUTOMATIC CONTROL

"There are many things in life which men ought to do, and much learned and scientific eloquence is repeatedly urged in favour of their doing them, but as indolence, indifference, and ignorance are not easily moved to exertion, the benefit must, if possible, be conferred without occasioning thought, trouble, or exertion to those who are to share in its advantages."

Thus wrote Tomlinson in 1850, on the need for automatic devices for ventilation and lightning protection.[22]

Some elementary controls had been previously used on boilers. The installation in St. George's Hall, Liverpool, designed by Dr D. B. Reid and erected between 1851 and 1854, is perhaps remarkable in that an alarm system was fitted to the steam boilers of a significant building. Ordinary mercury-in-glass thermometers were provided with electrical contacts in the stem: when the boiler became too hot, the circuit was completed and an alarm bell rang.[12]

Thermostatic controls and draught regulators were soon to be developed in America. Yet despite the progress, particularly in the application of controls to industrial processes, Dufton was still able to say, in 1941, in an address to the Newcomen Society:[7]

"It is difficult to understand the prejudice against automatic control. It is not many years ago that a President of the IHVE 'deprecated in his own practice the elaboration of automatic mechanisms because, in his view, they were not needed, and, in the second place, they were liable to get out of order... . In normal heating work, all that fancy work was not needed.'"

Neither was this a new view. In 1897, Picard said:[18]

"These devices are very complicated, their cost is very high, and their performance very uncertain, so it seems that they ought to be abandoned completely."

Yet Tomlinson was right in his assessment of human behaviour. Manual control of even the simplest system is almost always crude and wasteful of fuel; manual control of a large and complex air-conditioning plant would be all but impossible. So the situation today is quite different. No system is installed without at least a minimum of control, to ensure both safety and efficiency.

11.1 MEASURING DEVICES

The first recorded primitive effort to measure changes in temperature was in 1593, when Galileo Galilei devised his own "thermoscope":(1)

> "Galilei took a glass vessel about the size of a hen's egg, fitted to a tube the width of a straw, and about two spans long; he heated the glass bulb in his hands and turned the glass upside down so that the tube (could be) dipped in water contained in another vessel. As soon as the bulb cooled down the water rose in the tube the height of a span above the level of the vessel. This instrument he used to investigate degrees of heat and cold."

Galileo's arrangement was inverted by a French physician named Jean Rey, who filled the bulb with water and the stem with air, but it proved inaccurate because of evaporation from the open top of the stem.

In a series of experiments at the Accademia del Cimento in Florence, the Tuscan Grand Duke, Ferdinand II, used spirits of wine (a crude alcohol) in place of water, sealed the end of the tube, and marked off degrees with beads of glass.

However, it was left to Daniel Gabriel Fahrenheit to develop the first reliable thermometer. In 1724, he wrote:(1)

> "About ten year's ago I read in the *History of Sciences*... that the celebrated (Guillaume) Amontons, using a thermometer of his own invention, had discovered that water boils at a fixed degree of heat. I was at once inflamed with a great desire to make for myself a thermometer of the same sort, so that I might with my own eyes perceive this beautiful phenomenon of nature and be convinced of the truth of the experiment."

By comparison, crude but effective instruments for measuring humidity were available by the end of the 15th century. One of the earliest, called a "hygroscope" was described by the German Cardinal Nicolaus de Cusa:(2)

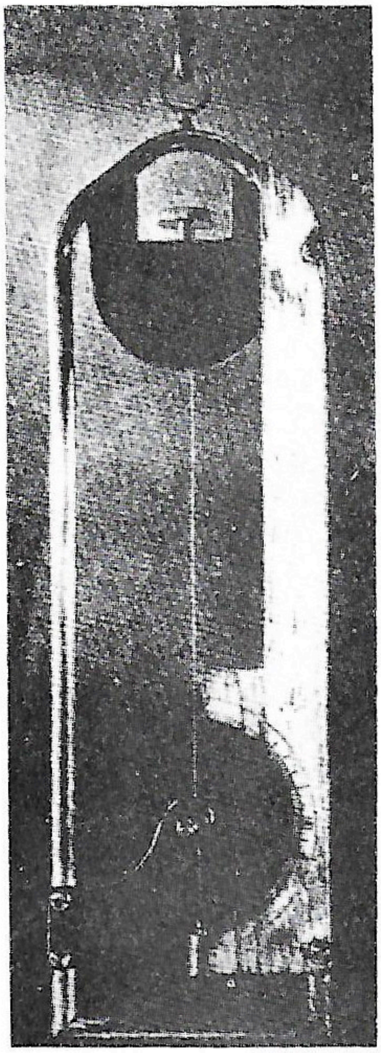
> "If you suspend from one side of a large balance a large quantity of wool, and from the other side stones, so that they weigh equally in dry air, then you will see that when the air inclines towards dampness, the weight of the wool increases, and when it tends to dryness, it decreases."

In England, during the 17th century, the philosopher-inventor Robert Hooke made a hygroscope that exploited the water-retaining properties "of the bristle of the wild oak".

The first hygrometer which makes use of the moisture absorbancy of human hair to measure atmospheric humidity was invented by Horace Bénédict de Saussure in 1780 (Fig. 11.1).

It was in the 18th century that attempts to determine the magnitude of different electrical and magnetic quantities began.

Oersted's discovery of the effect of the current in a wire on a nearby pivoted magnet (1820) was soon followed by Schweigger's "multiplier" (1821), and other forms of galvanometer. But, possibly the most fundamental of all electric measuring instruments was the "Wheatstone Bridge" which "historically takes precedence in the vast array of devices which sprang from Oersted's experiment of 1820". Its development has been described by Dunsheath in his *History of Electrical Engineering:*



(Fig. 11.1. Hair hygrometer (de Saussure, 1780).

"Within thirteen years Samuel Hunter Christie described a differential arrangement of conductors which formed the basis of Wheatstone's application in his 'Differential Resistance Measurer', published in his 1843 Bakerian lecture. In this lecture, Wheatstone unreservedly gave the credit for the idea to Christie but he made so many practical additions that the bridge became widely assigned to him and is now always known by his name."

Another important contribution, closely related to the Wheatstone Bridge, was the potentiometer devised by Poggendorff in 1841.

In the 20th century, with the development of automatic controls for heating, ventilating and air conditioning systems, the potentiometer was to form the basis of many electrical control systems, while both alternating and direct-current versions of the Wheatstone bridge would find their way into electronic controllers.

11.2 Temperature Control

A historical account of the development of the thermostat or heat governor has been given by A. R. J. Ramsey before the Newcomen Society.(19) The word "thermostat" was coined by Dr Ure in 1830, though temperature-sensitive devices had been in use for more than a century prior to this.

The prototype thermostat is probably that invented early in the 17th century by Cornelius Drebbel, a Dutch engineer. According to an account by Francis Bacon, Drebbel devised his temperature regulator only incidentally, "as an instrument to serve another purpose: alchemy. He believed he could transmute base metals to gold if he could keep the temperature of the process metal constant for a long time."

Drebbel's temperature regulator (Fig. 11.2) has been described as follows:(16)

> "Drebbel's apparatus consisted basically of a box with a fire at the bottom and above this an inner compartment containing air or alcohol with a U-shaped neck topped by mercury. As the temperature in the box rose, the increased pressure of the heated air or alcohol vapour pushed up the mercury, which in turn pushed up a rod; this mechanical force was applied to close a damper and throttle down the fire. Conversely, if the temperature in the box fell below the desired level, the gas pressure was reduced, the mercury dropped and the mechanical linkage opened the damper."

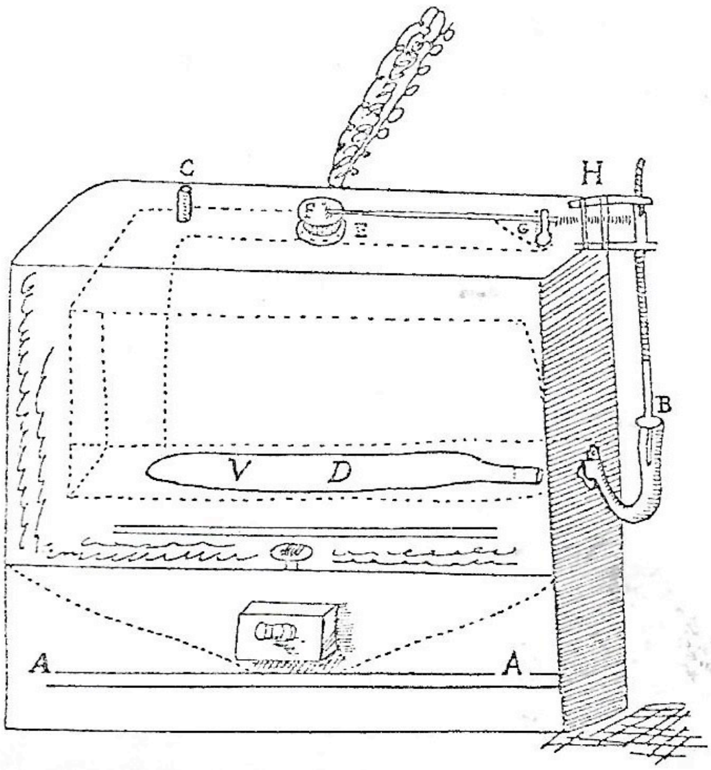


Fig. 11.2. Drebbel's thermostat (early 17th century).

This regulator seems to have worked successfully, for Members of the Royal Society of London, including Robert Boyle, Christopher Wren, and in the following generation Robert Hooke, showed interest in it.

Harrison's compensated grid-iron pendulum was invented in 1726. In 1761, he produced the first device incorporating a true bimetallic strip. These early bimetals were manufactured by rivetting, but sweating or welding were used before the end of the 19th century. The application of bimetals soon spread. Bonnemain used a Harrison device in 1777 to control the temperature of both buildings and incubators — probably the first attempt to control space-heating automatically. The sensitive element was mechanically linked to the ash-pit door of a boiler, and served to regulate the rate of combustion. Ure designed an air-heating stove with a bimetallic thermostat, though there is no record of it being used commercially.

Arnott was more successful with his "thermometer stove" described in 1836. In one design he used a long bimetallic strip, one end of which was fixed to the casing of the stove and the other was attached to the combustion air damper. Other regulators described by Arnott relied upon the expansion of air in a tube closed by mercury: a float on the mercury surface was linked to the damper. All these devices controlled the temperature inside the stove casing, not that of the room. There was also in existence a well-known means of adjusting the temperature of bakers' ovens by a self-acting thermometer.

Carleton Nason in 1880 and J. T. Hawkins in 1888 used a bimetallic helix for temperature control. In Hawkins' design, the helix was wound round the return pipe, the brass being in contact with the pipe and the steel exposed to the air.

James Kewley's heat governor, patented in 1816, was based on a different principle. It made use of the fact that mercury and alcohol expand and contract at different rates as the temperature changes.

A. M. Perkins used a draught regulator on the second version of his high pressure system: it is described in his book of 1840. It relied upon the linear expansion of the flow pipe to open or close the furnace damper. A nut on the pipe served to adjust the setting of the regulator.

The "Nason" regulator, used in America in about 1868, appears to have been rather similar in principle — it used the differential expansion of the flow pipe and a rod in the air, to keep the flow temperature constant. This was also used later by G. W. Blake of New York; and by Grouvelle in France to control either the steam supply or the position of the furnace damper. Debesson remarked that this type of control was both insensitive and unreliable in its calibration.

The Pascal Ironworks of Philadelphia used a float valve in an expansion tank to control the chimney and ash-pit dampers, in about 1870 (Fig. 11.3). A variant of this method, using a diaphragm, was due to E. A. Haynes. It had considerable time lag due to the volume of water in the vessels C and D. Baldwin noted:

> "The principle involved, however, is a good one, and is deserving of close consideration with regard to its practical development."

Appold's apparatus for regulating temperature and keeping the air in a building at any desired degree of moisture, is described in the *Proceedings of the Royal Society of London* (1866-67) (Fig. 11.4). The operation of Appold's apparatus is explained as follows:[4]

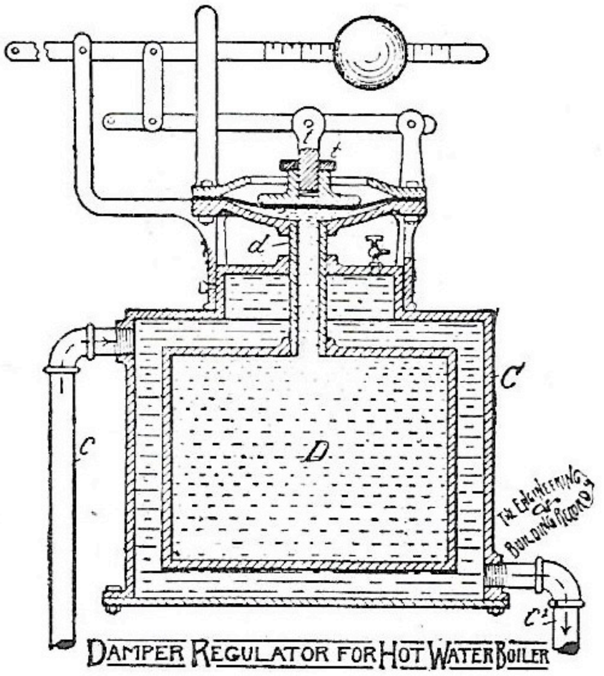


Fig. 11.3. Damper regulator (Pascal Ironworks,(1870).

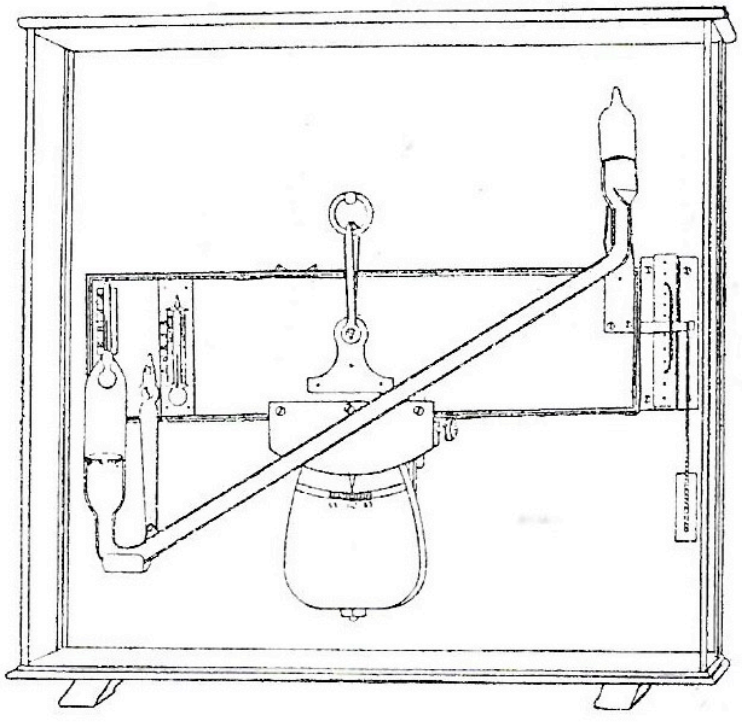


Fig. 11.4. Appold's apparatus for regulating temperature and keeping the air in a building at any desired degree of moisture (1866).

> "This instrument consists of a glass tube having bulbs at each end. The tube is filled, as also about half of each bulb, with mercury, the lower bulb containing ether to the depth of half an inch, which floats on the mercury. The tube is secured to a plate of boxwood, and supported on knife edges, on which it turns freely. At the end of the plate, underneath the highest bulb, is a lever to which a string is attached. This string is carried by means of bell cranks to the supply valve of a gas stove or the damper of a furnace.
>
> The instrument acts in the following manner:
>
> Supposing the stove to be lighted and to have raised the temperature more than is required, the heat will convert a portion of the ether in the lower bulb into vapour. The expansion of this vapour drives a quantity of the mercury out of the bulb underneath it through the tube into the upper bulb. The end to which the mercury has been driven being thus rendered the heaviest, falls, and motion being communicated by the lever to the string, this closes the supply valve or damper of the stove or furnace. Of course, if this should be carried beyond the required extent, the reverse action will take place.
>
> A weight in the centre of the plate, the position of which is regulated by a milled-head screw shown at the side, serves to alter the centre of gravity of the whole apparatus. The value of the motion of this weight being carefully ascertained, a scale is engraved upon it. By moving this weight, according to a scale engraved on it, the instrument may be set so as to maintain any desired temperature in the building in which it is fixed.
>
> The range of action of the instrument is from 54° to 66°F, and with a change of temperature of 1 degree it has the power to raise one ounce 3 inches."

In 1881, Hearson developed a capsule containing a volatile liquid, the capsule being mechanically coupled to the valve operating gear. According to Debesson,(6) this type, filled with alcohol or ether, was that most commonly used in France in the early years of this century. He mentions the German Wormatia and the American Lawler types; the German Buderus control, which was similar, was filled with aqua-ammonia. Bohain (Paris) patented a control of this type in 1900. The Geneste-Herscher controller(18) used the liquid phial to control steam supply: it seems to have been a room thermostat, since remote operation was possible. There were important defects in this type of sensor — failure of the diaphragm, and leakage of the working fluid. Debesson had a low opinion of the then existing controls, for he wrote:(6)

> "Let us hasten to say, and to regret deeply, that no simple and really practical temperature regulator yet exists, and that those ingenious systems are generally complicated, very costly and cannot give an assured performance."

The National Radiator Company's "Sylphon" control was a liquid-filled bellows. It was reported to give good results, and was less defective and less prone to leakage than the volatile fluid devices. The capsule and thermal bellows have been further developed, notably by the Kelvinator Corporation in 1923, when the bellows were charged with liquid, gas or vapour. The use of bellows for pressure measurement had been suggested, if not used, in 1885.

Devices for controlling water temperature were introduced into Swiss practice in the early 1880's.(3)

Writing in 1897, Dye(8) stated that room thermostats were not at that time in use in Britain for controlling central heating systems; he knew "that two or three such devices were then in use in America", though draught regulators were becoming commoner in Britain. S. Naylor(17) describes a number of these, but preferred a mercurial one for use with high-pressure steam heating.

Picard (1897) notes that electrical contacts in a Bourdon gauge had been used to operate an alarm in a Perkins' system. An alternative was to use a Bourdon tube, acting directly on a valve controlling the heating fluid (Fig. 11.5). A simple manual adjustment could be made. It was unfortunately too costly for general use in dwellings.

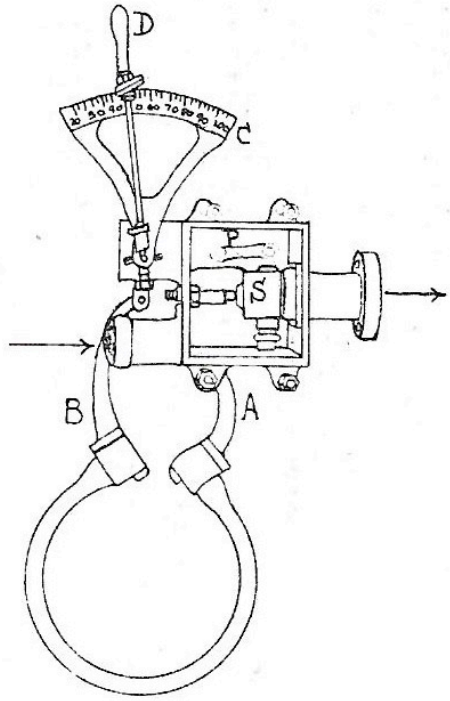


Fig. 11.5. Direct-acting Bourdon-tube thermostat.

11.3 ELECTRICAL CONTROLS

About 1885, Perret had proposed an electrical control system. This was based on a maximum-minimum thermometer with two contacts. When the temperature rose to the upper setting, or fell below the other, a current passed (in one direction or the other) through an electro-magnet which closed or opened a damper at the warm-air supply outlet. The performance was said to be poor.

In 1883, Albert M. Butz of Minneapolis developed a crude thermostat made of a strip of hard rubber cemented to a strip of brass. This thermostat was equipped with contacts arranged to control an equally crude damper motor. The hand-wound spring-powered motor was designed to control the rate of burning coal in a furnace or boiler by opening and closing a flapper type draught damper.

In 1885 Butz formed the Consolidated Temperature Controlling Company, which was re-organised and re-named the Electric Thermostat Company in 1889. The company was later to become the Minneapolis Heat Regulator Company (and later after various name changes — Honeywell Limited).

The Kaeferle thermostat (Hanover) employed an electrical contact thermometer, based on a bimetal strip, and coupled to an electro-magnetic valve. It was said to have a differential of 1°C.

It is apparent that the use of controls had reached a fair level of sophistication in Europe. The Budapest Stock Exchange, built in 1905 included a monitoring and control centre.(15) Electric contact thermometers controlled the steam supply to the heating coils; air dampers were remotely operated by wires and pulleys from the control centres, and the air volume was controlled by varying the fan speed, which was indicated by signal lamps. The plant served a building of some 100000 m^3; it had a central control and operating panel, and was worked by one engineer and two stokers. Electric resistance thermometers were used for monitoring. W. N. Haden said he had seen similar equipment in the Capitol in Washington. This was in 1906, when he was pressing the case for room thermostats, adding that in the USA these would always be included in a good job. (The controls then were pneumatically operated.) He seems to have failed in his plea, for controls were seldom used in the UK until after World War I.

Electric controls were in limited use in the UK in the late 1930's. Earlier, in 1923, Benham's were fitting thermostats for electric boilers and bath heaters, to be used with a relay-operated mercury switch. There was also a cheap model operating on the principle of the maximum-minimum thermometer. Three Leclanché cells were recommended for operating these devices. The Rheostatic Company made a bimetallic thermostat in 1928 for controlling an electric heating installation by Young, Austen and Young.(10) The use of the accelerator heater in bimetal thermostats, to improve the working characteristics, was known in America before 1928; Rheostatic (UK) and Sauter (Switzerland) adopted them in 1932 and 1935 respectively. From 1934 on, there was a significant use of bimetal thermostats for electric tubular heaters.

An important development was the magnetically controlled micro-gap switch, patented by Rheostatic Company in about 1926, and used for their first room thermostat in 1927. The micro-gap switch gave rapid opening, avoiding arcing and contact welding.(10)

By comparison, pneumatic controls were in use in industrial processes in the UK prior to 1930, but were not applied to heating and ventilating installations in significant numbers until after World War II (indeed, according to F. M. H. Taylor,(21) only in 1959, when high-velocity air conditioning was introduced into the UK).

11.4 PNEUMATIC CONTROL

According to Hollman, W. S. Johnson, a physics teacher from Wisconsin, was the first to use a pneumatic thermostat in about 1880.(11) The Powers patent (USA, 1889) used vapour pressure to move a diaphragm, the other side of which was connected by a tube to the actual regulating mechanism. The first application seems to have been in 1901. Little development took place until compressed air was used as the source of power. An electro-pneumatic system (Fig. 11.6) was described in *The Engineering Record*, of 9th August, 1890, having been installed in the Mechanics Bank Building in New York:(4)

> "This thermostat may be set to work at any temperature, and is claimed to operate satisfactorily within a range of 1 degree. The figure shows the back of the instrument that is mounted on a brass bed plate P, to which are fixed the standards A B B that carry the mechanism and have holes Z Z for attaching to the wall or other convenient support. One end of the lever C is connected to A by the pivot D, and the other end by a screw F tapped through lug E.
>
> The expansion bar I is made of a plate of brass and a plate of rubber riveted together and attached to lever C at pivot D.

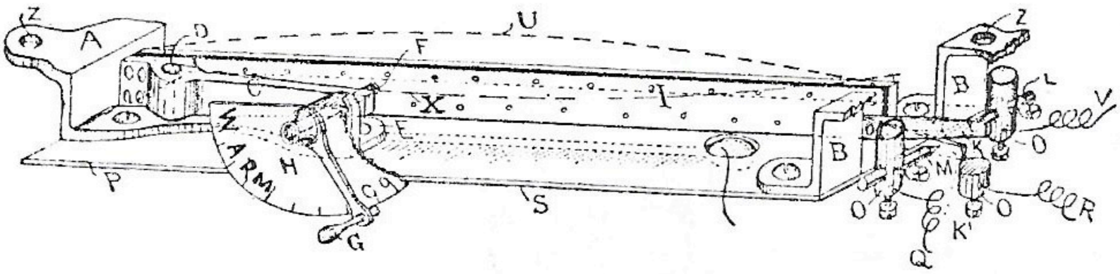


Fig. 11.6. Electro-pneumatic control system — the electric thermostat (*ca.* 1890).

The other end of the bar is free and carries a platinum contact bar K. O O O are bind posts fixed on plate B, and receiving the circuit wires Q R V, and the adjustable contact points L and M. The rubber and brass in bar I expand and contact differently for the same differences of temperature, so that a rise in temperature will make it bow out to the (exaggerated) position U, and throw K to K' in contact with M, thus completing the electric circuit from R through Q and opening the valve.

A fall in the temperature bows out I in the opposite direction to the (exaggerated) position X and makes contact between K and L, thus completing the circuit from R to V and closing the valve.

By moving lever G along the scale H, screw F is turned and swings lever C on its pivot D so as to set the bar K nearer to either L or M and make the thermostat operate at any desired temperature within 15 degrees of that originally provided for".

The electricity supply was provided by a battery, and in order to prolong its life when the armatures reached their extreme positions the current through the conductors was switched off by movement of the contact springs. The steam valve itself was operated by compressed air fed to the side of a circular rubber diaphragm. With air pressure removed, a spiral spring returned the valve to the open position. On some models the valve stem passed out through the top of the valve, through a stuffing box, and was fitted with a hand wheel to give independent manual regulation.

Johnson soon turned to an entirely pneumatic system (Fig. 11.7). The positive type thermostat was described by Jones at the IHVE Annual General Meeting of 1912:

"A is a wall plate which is fastened to the wall and is generally put in place before the walls are plastered and is therefore left flush with the surface of the wall. A brass block, B, serves for the attachment of the thermostat to the air pipes, which are usually concealed behind the wall surface, in the plaster. Pipe C leads from the air compressor, and pipe D leads to the air motor at the valve or damper which it operates.

E E, are two pin valves used to regulate the air. The upper one is used to shut off the main air supply (if it is desired at any time to remove the thermostat); the lower one is used to retard the air going to the motor on the valve or damper when it is desired that they should move slowly.

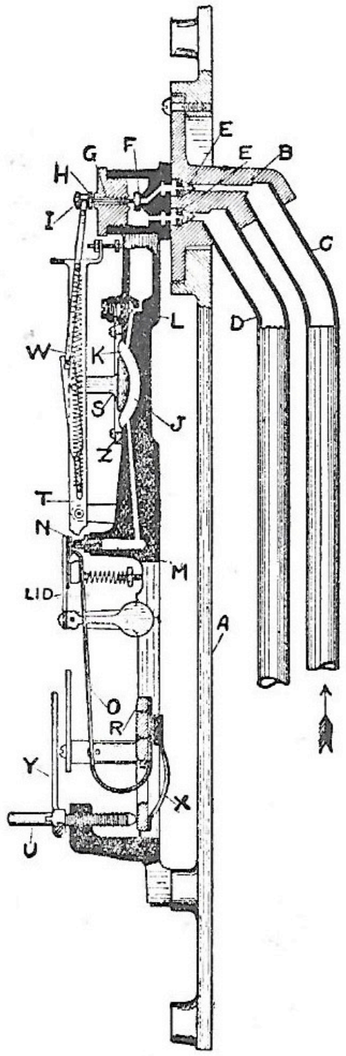


Fig. 11.7. Johnson pneumatic bimetal thermostat (*ca.* 1912).

From the valve E, the air is led up the crooked passage shown to the air valve F. When in the position shown it will be seen that the air can go no further. F is attached to the stem, G, which passes up through the outlet, H, and has the grooved head, I. Now, if F be moved up to the inside opening of H, it will close the opening and will open the pipe C. It is evident that since F is against H, this air cannot escape to the opening, but it *can* pass to the pipe D, and thus to the air motor or diaphragm valve on the steam or hot water (or damper) and close same."

For operation to be automatic the valve F must respond to movements of the thermostat strip caused by temperature changes. This is achieved by a small "air motor" with a rubber diaphragm.

This so-called "positive" thermostat was designed for steam service. Other types were designed to provide a "graduate" action, so that the valve or damper being controlled operated gradually. Many of these positive thermostats were used together with a diaphragm valve for the control of radiator systems.

The National Radiator Company (1900) used the expansion of a vulcanised rubber tube, with compressed air transmission to the regulator. The Powers regulator employed a liquid-filled aneroid capsule, to control the boiler damper.

Grouvelle and Arquembourg developed a servo system with hydraulic transmission to the controlled valves in about 1904. They also used compressed air, though this was less liked by Debesson.[6] The control mechanism could be arranged to operate an electric alarm. This equipment was to be used in the central boiler house of a group heating scheme or hospital complex, the separate buildings having their own control valves. Grouvelle showed a thermo-regulator based on vacuum servos at the Liège exposition of 1900: it worked only with steam systems operating at 0.2 kg and above.

Debesson illustrates a thermo-regulator of which the sensitive element was an expansible tube. Movement of the tube controlled the access of compressed air to a servo-motor. Debesson notes that town's gas may be used in place of the compressed air as the working fluid. It is surprising that the gas escaping from the thermostat was discharged into the chimney; and Debesson himself remarks that it would be better to discharge it into the furnace (Fig. 11.8).

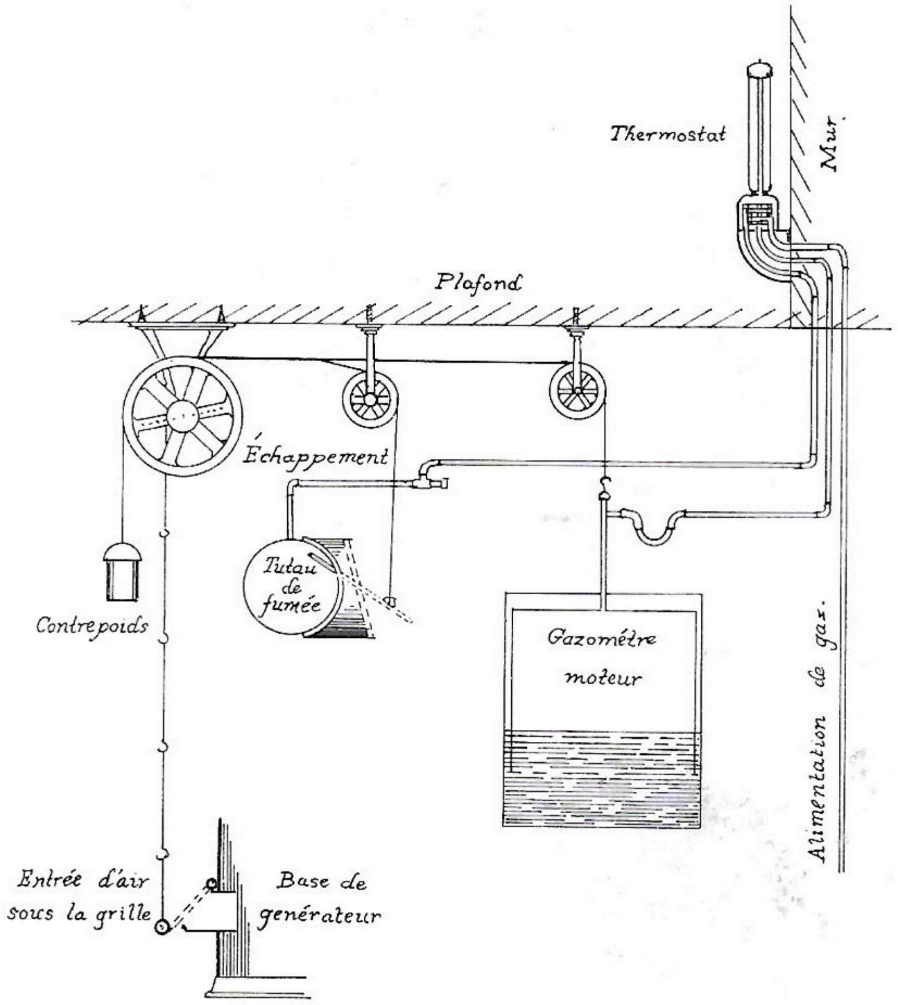


Fig. 11.8. Primary air control/draught control by thermostat operating on town's gas (*ca.* 1900).

By 1910, motorised controls were coming into general use in America. Professor Carpenter mentions clockwork, electric, hydraulic and pneumatic drive, and he showed, by examination of fuel consumption records of three buildings, that thermostatic control saved about 35% of the fuel.

The US Treasury Department, in its 1912 edition of the Guide to the design of mechanical services in Federal buildings, urged the use of automatic controls in all cases. The pneumatic system was preferred to electric controls. The cost at that time was given as $26 per thermostat, $22 for each damper controlled, and $20 for each steam or water valve controlled.

The introduction of power-operated systems meant that the sensor and the operating device could be separated by appreciable distances, since there was no need for any mechanical connection between the two, and there was no need for the sensor to develop enough power to operate the valves or dampers. This was a significant development, and was indeed essential if fully integrated control systems were to be applied to large buildings.

It is apparent that, in spite of the early efforts by European engineers, the major development and use of controls took place in the USA, followed much later by Germany. French engineers used, very largely, German control equipment, though there were also French designs on the market. In spite of some early devices and applications, British engineers generally made little use of controls (apart from draught regulators) until the 1930's. Hollman[11] reports that a German firm made a pneumatic thermostat in 1925, and from then on many industrial ventilation plants had pneumatic controls, but it was not until about 1935 that they were at all widely used in heating and ventilating plant.* He estimated that in 1965, some 80% of heating and ventilating systems in the USA were fitted with pneumatic controls (the remainder being electric or electronic), whereas in Germany only about 20% were so fitted.

11.5 VALVES

A simple valve, in which an orifice is progressively opened as the valve head is turned, has a very non-linear characteristic, i.e. the flow through the valve is by no means proportional to the valve opening. The situation is made worse, in the case of radiators, because the heat output is hardly affected by diminution of flow rate down to perhaps half the normal flow. A simple valve, therefore, is little better than an on-off device, and is of little use for flow or output regulation. The performance of radiator valves was studied at Charlottenburg in 1919, and the importance of linear regulation of heat output was soon recognised. A design of valve having this characteristic was illustrated by Brabbée. Much ingenuity has since been spent on producing the so-called "characterised" valve.

Two recent developments in controlling the output of individual radiators are worth noting. One is the solenoid or magnetic valve operated by a room thermostat, to control the flow of water through a radiator. This was certainly in use in Britain in 1930: it had been introduced from America. The second is the thermostatic radiator valve, of which there are several current designs. It may have been of Danish origin: it certainly became widespread in Europe around 1960, and rather later in Britain when domestic central heating became usual. In some patterns, the sensing element is incorporated in the valve body, when it may be affected by water temperature as well as air temperature. In others, the element is a phial which can be placed in the room remote from the valve itself. Similar devices are

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*F. M. H. Taylor[21] stated that controls of any kind were hardly used in Germany before 1945; that French practice was behind that in Britain; but that in Sweden control application was as advanced as in the USA.

used to control domestic hot water supply temperatures — the valve is placed in the flow pipe to the storage vessel and the sensing head in the cylinder itself. When the element is satisfied, the valve closes to shut off the flow of hot water from the boiler to the vessel.

An American, F. C. Leonard devised a thermostatic mixing valve (in which hot and cold water were mixed to give a constant-temperature supply) for use with bath showers in 1913. This seems to have been its principal (if not sole) use for many years. About 1935, Sauter in Switzerland began to apply mixing valves to heating systems, but they do not appear to have been widely used until after World War II. The function here was to enable the flow temperature of a system to be varied in accordance with demand by mixing the constant temperature boiler flow with cooler water returning to the boiler from the system.

The German firm of Wobig produced a thermostatic 4-way mixing valve for use on radiators in 1-pipe systems (1970). It was claimed that the good control of radiator temperature and heat output enabled smaller radiators to be used.

11.6 HUMIDITY CONTROL

Leslie made a differential wet- and dry-bulb thermometer to indicate (but not control) humidity. The wet-bulb depression, or the wet-bulb temperature, forms the basis for many present-day humidity controllers. Barker described a type of humidity controller in 1904 (*Proc. IHVE*):

> "A vessel is provided of such form that the surface of the water can be instantly altered by means of a regulator. As the temperature in the air chamber (plenum) varies with the required conditions, so the water surface is altered to suit, it being well known that evaporation takes place only in accordance with the surface exposed."

This seems, now, to have been only a humidifying device, incapable of precise control. No other mode of humidity control occurs in the principal texts published before that date.

In a classic paper(5) presented to the Annual Meeting of the American Society of Mechanical Engineers in 1911, Willis H. Carrier and Frank L. Busey set out the principles of humidity control by the Dewpoint method:

> "This system is applicable only where the absolute moisture content of the air in a room is unaffected to any great extent by extraneous sources of moisture supply or by moisture absorption. It depends upon supplying the enclosure with conditioned air having a definite dewpoint and maintaining a pre-determined relationship between this dewpoint temperature and room temperature."

A typical dewpoint thermostat of the period (Fig. 11.9) comprises an outer "expansive" member A made of brass, surrounding an inner "non-expansive" member B of nickel steel, both firmly connected at C. At the other end is a bronze valve D, ground to fit the adjustable valve E. Compressed air is supplied at F, and enters the annual chamber G. As the outer member A expands with a rise in temperature, valve D moves off its seat, allowing compressed air to pass through H to actuate a diaphragm valve (controlling the temperature of spray water in an air washer). J is an adjustable vent which releases the air pressure on the diaphragm when D closes on a fall in temperature.

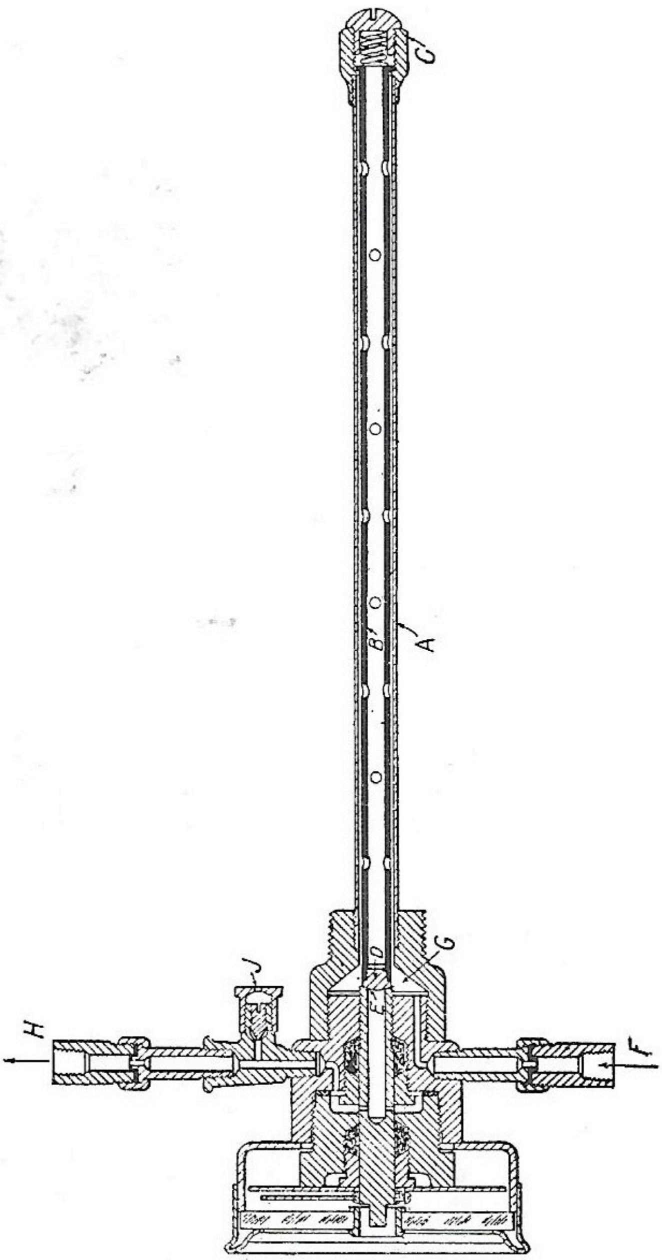

Fig. 11.9. Dewpoint thermostat (1911).

A development of this dewpoint thermostat was the differential thermostat, which employed two expansible members acting conjointly. As air conditioning systems increased in size the fluid differential thermostat was designed to cater for use where several floors were conditioned from one central plant, but where some independent control was required.

Carrier found there were many applications where "the dewpoint system of humidity control cannot be applied to advantage". So he developed the differential hygrostat (Fig. 11.10). This incorporates an expansive dry-bulb member and a wet-bulb member (constructed of hard rubber tube). Carrier recognised that "the difference between the dry and wet bulb temperature for a given percent of humidity is not constant at different dry-bulb temperatures", and made clever use of differential screw threads in the mechanism to compensate for this.

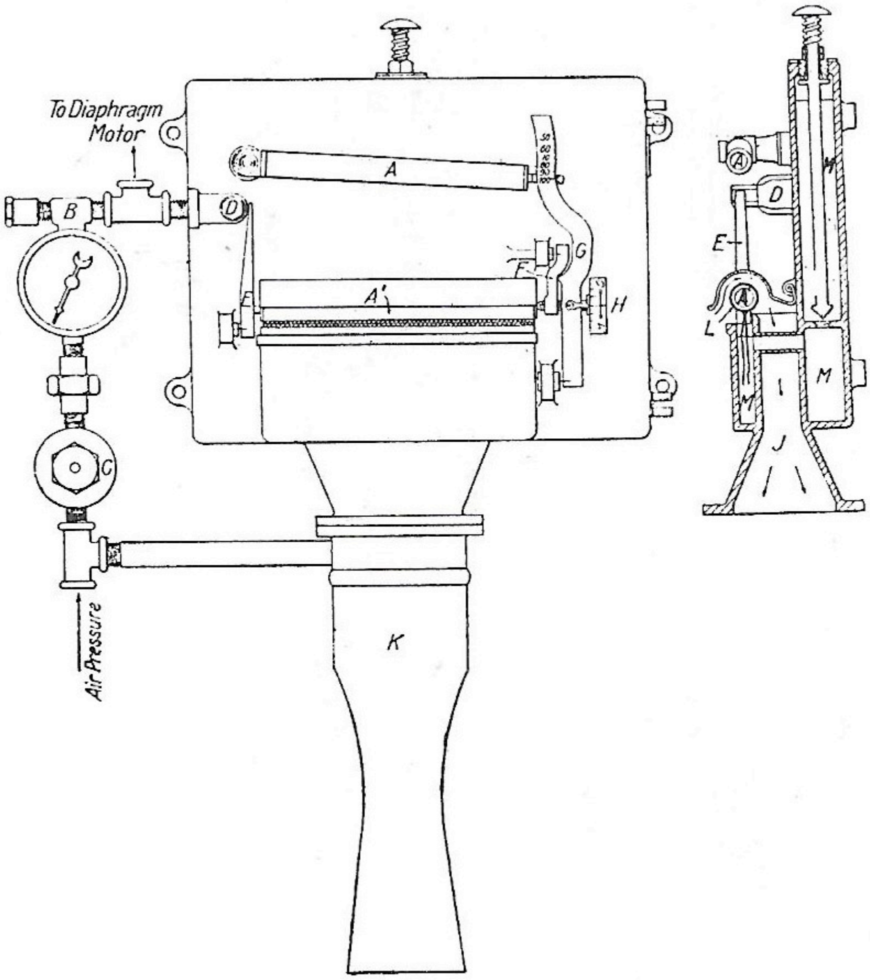

Fig. 11.10. Carrier differential hygrostat (1911).

An improved form of hygrostat was operated by the relative pressures of a volatile liquid (sulphur dioxide), subjected to the wet-and dry-bulb temperatures in the so-called "vapour pressure hygrostat", acting through suitable diaphragms on a common lever at variable distances from the fulcrum. Carrier went on to apply the same principles in the design and construction of his recording hygrometer.

11.2 BOILER CONTROLS

It has already been noticed that solid-fuel boilers of the magazine type were controlled by the operation of ash-pit or flue dampers in response to the demands of some form of thermostat. The boilers were, of course, charged manually. Other boilers were controlled by the stoker himself, who would adjust the rate of charging and the damper settings to suit the load.

Automatic stokers were developed in America — probably to reduce labour costs — and were introduced into British practice by Ashwell and Nesbit in 1933. Attempts were made at about the same time by Beeston to apply thermostatic control to the forced-draught fans of solid-fuel boilers. These were not always satisfactory, and there were occasional explosions, due to the building up of unburnt gases in the combustion chamber when the fan was switched off. The Honeywell 802 regulator was also used on solid-fuel boilers. All these controls were intended to maintain a constant flow temperature.

Thermostatic control of small gravity-fed domestic solid-fuel boilers was available in Britain *ca.* 1950, at about the time when domestic central heating was beginning to take hold. This control operated on the air supply damper (just as for the early 19th century stoves). Its use became especially important with the introduction by BCURA of the small-bore heating system, where the small liquid volume rendered adequate precautions against overheating and boiling imperative.

Ready availability of oil and natural gas in America led to the use of these fuels in place of coal and coke (mainly due to their convenience and ease of control) before World War II. But elsewhere, solid fuel continued to be widely used until well into the 1950's. The production of town's gas yielded a surplus of coke, for which heating provided a ready market. Gas had been used on a relatively small scale in the late 1930's, and F. M. H. Taylor of Thermocontrol Ltd. introduced a series of controls for gas burners. One was a magnetic-plus-diagram valve to control the gas supply: its characteristic was rapid shut-off but gradual increase of gas supply, to avoid problems arising if the full gas supply were suddenly turned on. (At that time, ignition was invariably by means of a pilot flame.) The second was a device to cut off the primary air supply when the gas was off. It was only supplied as a special feature, in spite of its obvious value in reducing stand-by losses of heat from the boiler surfaces.[21]

In the interests of economy, it is desirable to vary the flow temperature of a heating system in accordance with the outdoor temperature. The outdoor compensator (Variator) was pioneered in the UK; it was manufactured by Drayton Controls *ca.* 1933, for application to solid-fuel boilers (to the boiler damper of coke boilers, or to the automatic stoker of coal boilers). The use of electricity to power the controls of gas-fired boilers was a British innovation, and one which was significant because of the competition between the gas and electric utilities.[21] However, power failure could cause problems with motorised controls, until the Barber-Colman stalling motor, the Teddington hydraulic motor and the heat motor were introduced.

11.8 STEAM PRESSURE CONTROLLERS

Kauffer & Co. (Mainz) in 1884 patented a pressure regulator for low-pressure steam. Changes in boiler pressure caused the water level in a vessel to vary, allowing more or less primary air to the space beneath the boiler grate. It was of little interest, except to show that German engineers were seeking regulators better than the membrane devices then in use in America. Another ingenious device was employed by Monnot in 1884-5 in some Paris schools (Fig. 11.11).

Pressure regulators for high-pressure steam also made use of a liquid column — in this case, mercury.[6] One of the first was due to Koerting (1890): a float on a column of mercury responded to variations of pressure, and controlled the air supply to the boiler (Fig. 11.12). A modified form also operated the flue damper: this regulator was capable of adjustment to any desired steam pressure (Fig. 11.13).

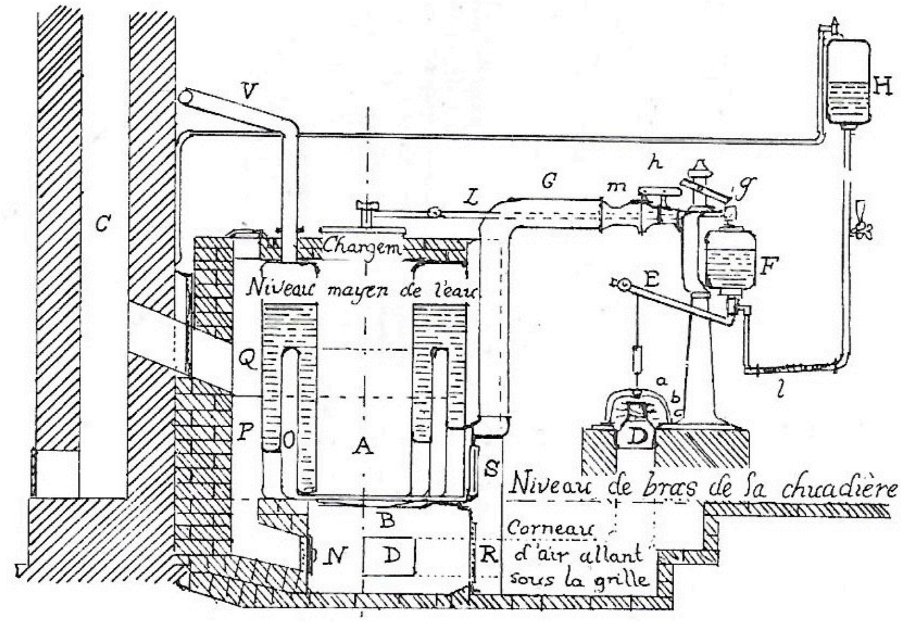

Fig. 11.11. Primary air controller for low-pressure steam boilers (Monnot, 1884).

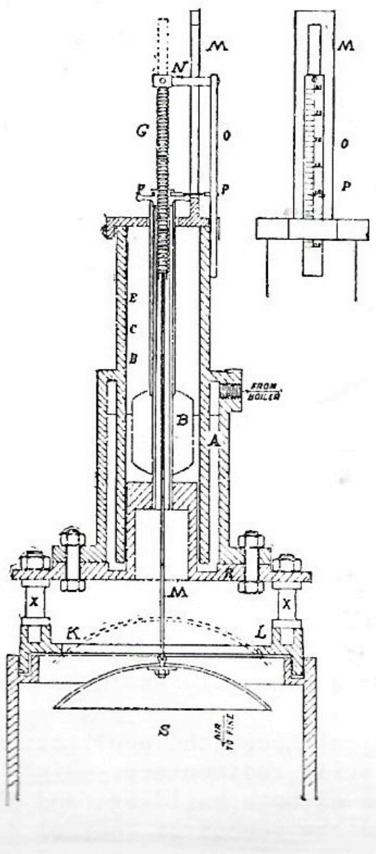

Fig. 11.12. Koerting primary air controller (mercury) for steam boilers (1890).

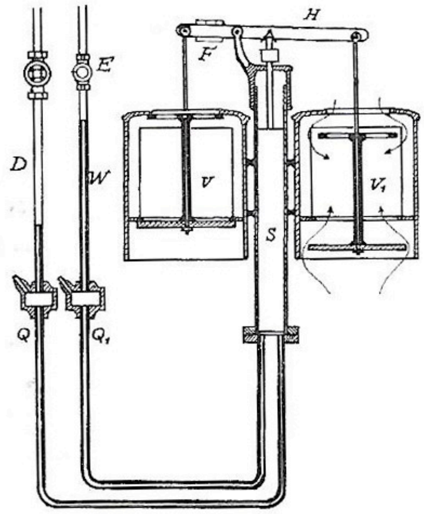

Fig. 11.13. Koerting primary air controller (1906).

For high and medium pressure steam, Debesson describes a series of pressure-reducing valves (pressure controllers) manufactured by such firms as Schaeffer and Budenberg (Germany), Foster, Belfield, Kisley (America) and Muller and Roger, Belleville, Deviau, Grouvelle and Arquembourg in France. French designs were, he said, "infiniment plus soignés et plus sérieux".[6] Many of the simpler devices relied on expansion through an orifice, controlled by a counterweight. Two by Kaeferle (Hanover) and Geneste-Herscher (France, 1888) were thermostatically controlled, using the principle of the expansion of mercury contained in a "thermometer" well. All these had to be adjusted by hand, and could not be used for remote control.

Two principal methods of control (both proprietary) were in use for steam systems. One was the Dunham differential control in which capacity control was exercised by varying the steam temperature and flow. At maximum load, the steam pressure was about 2 lb/in^2g (103°C); at minimum load (about 57% of the maximum), it was 25 in Hg abs. (45°C). In the Webster Moderator control an outdoor thermostat controlled the steam valve to produce a pressure difference across metering orifices at each radiator or heating coil, which then gave a steam flow appropriate to demand.

11.9 CONTROL THEORY

Control applications outran the development of control theory. The Nyquist diagram of transfer loci was published in 1932 (*Bell System Tech. J.* 11,126), and in 1936 Callendar, Hartree *et al.* gave a mathematical analysis of a control system with time lag and dead time. Yet Eckmann wrote in 1945:[9]

> "The last 30 years have been a period of great progress in the field of automatic control and automatic regulation... . Instrumentation and automatic control have progressed to the development of sophisticated mechanisms without a parallel development of a generally useful foundation of theory".

The position has now changed, although the application of the theory to the control of heating installations is still rudimentary, mainly because of the lack of precise data on the dynamic behaviour of both buildings and plant components, and of the complexity of the systems and the number of control devices necessary in a large installation.

Simple on-off controls exhibit undesirable characteristics — over- and undershoot and offset. In order to remove the first of these defects, the accelerator heater was first used, with bimetal thermostats, and this had the effect of speeding up the operation on rising temperature, and so reducing overshoot. Proportional reset (in which the set point is adjusted in relation to the load) was employed in the USA to eliminate offset. Rather later (in 1955) Sauter and Satchwell's Duotronic controls incorporated proportional and integral control to overcome both offset and hunting.

11.10 OPTIMUM START CONTROL

With manual firing of solid-fuel boilers — the normal situation in the early 20th century — it was usual to run the heating system only during the hours of occupation, and for a short period before. (It will be recalled that Picard gave a qualitative discussion of the pre-heating time needed).

Clock control of the hours of operation of a boiler system is now commonplace. In 1930, Ideal used a clock-controlled damper on solid-fuel boilers. Time-switch control of larger systems was sufficiently novel in the UK to be thought worthy of a paper to IHVE in 1954-5.

After automatic stoking and thermostatic control had been introduced, it became possible to run the system continuously and safely without attendance. Moreover, the high thermal capacity of the structures then being built rendered the internal temperature fairly stable, so that the extra fuel used was relatively small (perhaps 5 or 10%).

Nevertheless, the potential for fuel saving by intermittent operation (and particularly by week-end shut-down) continued to interest engineers in Britain and France — possibly because of the rather milder winters and because of the lack of use of automatic controls. The practice was to start the plant some hours (usually 3 or 4) before occupation commenced, and to shut down at the end of the building use. The start time was fixed, though in theory it could be varied from time to time as weather conditions changed. Electric time switches were normally used to control the commencement of firing and its shut-down.

In the structures then usual — which were massive and thermally inert — it was possible to accept a fixed start time, and indeed to use the same preheat period in almost all buildings. In the late 1940's there was a fundamental change in building design, with the advent of curtain-wall and highly glazed structures. The change in structure resulted in a building which was considerably more responsive: it cools more rapidly, and can be warmed more quickly, and can yield greater fuel savings from intermittent heating, than its pre-war counterpart.

Theoretical studies by Cadiergues *et al.* in France and by E. Harrison in Britain paved the way to a more detailed understanding of the problems. These were followed by experimental studies in a variety of buildings carried out by HVRA, which culminated in a design guide relating the maximum power of the heating plant, the thermal capacity of the building and the necessary preheating time, at a range of outdoor temperatures. The outdoor temperature and the inertia of the building determine the overnight cooling; this, with the inertia and power of the plant determine the necessary preheating. HVRA devised a method of varying the preheat time by sensing the internal temperature of the building, but it was never developed to the commercial stage. Honeywell Ltd. applied the HVRA findings and designed a satisfactory control to give a variable time start.(14) Although this control was first marketed in about 1970, the energy crisis of 1973-4 provided the stimulus needed for its wide use. The British Property Services Agency demonstrated substantial fuel savings when optimum start controllers were fitted to existing buildings (though it is probable that much of the economy was due to a general upgrading of the control system and operating schedules). Recent work (again by HVRA) suggests that the real saving due to substituting variable start for fixed time start is probably no more than about 10%. In 1979, microprocessor-based optimum start controllers were introduced commercially.

Off-peak electric thermal storage posed special control problems. In essence, energy is supplied at night into a storage medium. All storage heaters have the common characteristic that the quantity of heat which can be stored is limited; moreover, in floor heating and uncontrolled block heaters, the output is practically constant irrespective of heat demand. Attempts were made to adjust the energy input to correspond with demand, and to restrict the supply to the final hours of the charging period. Thermostats were incorporated in the floor to limit the floor temperature for comfort reasons. Weather forecasting was called in, in what was a vain attempt to supply energy sufficient to meet an anticipated load.

A controller introduced by Sangamo Weston in 1962 was designed to overcome some of the difficulties.[23] Its principal component was a well-insulated block having high thermal capacity; it incorporates a heater element (2 W) and a thermostatic switch. It is mounted on the outside of the building, and the temperature of the block depends both on the heater current and on the external cooling conditions: it thus simulates in some degree the behaviour of the building. In use, the heater is operative for 11 h from 7 a.m. and the temperature reached at switch-off depends both on the initial temperature and the rate of cooling. When the unit cools to 16°C the power is switched on to the building heating system: the time taken for the unit to cool to 16°C depends on the meteorological conditions, and the total system charging period is thus adjusted to correspond with the external temperature, sun, wind and rain.

The unit "remembers" the weather over a period of a day or so, and it adjusts the charging period to be as short (and as late) as possible, consistent with ensuring a full charge at the end of the off-peak period.

The controlled output heaters circumvented these problems. Provided the heat store is sufficient to meet the maximum demand, the output can be controlled by a room thermostat governing the operation of the air fan.

11.11 ELECTRONIC CONTROLS

In 1904, Ambrose Fleming, drawing on the earlier work of Edison and J. J. Thomson, invented the diode; but it was the addition of a third electrode (the grid) by de Forest in 1906 which gave the thermionic valve its most valuable feature — the ability to amplify a signal. However, despite this advance, electronic controls only started to be considered for possible application in heating and air-conditioning equipment from around 1938. In 1946, Jackson, in a paper to the IHVE[13] stated:

> "... there is as yet no general acceptance of electronics for the purposes of heating and ventilation... . The general trend in industrial measurement and control both in the United States, where progress has been spectacular, and on the Continent shows that electronic applications, if not fully established, cannot be neglected."

Electronic devices were used in the UK for control of building services and equipment from around the mid-1950's, particularly for boiler control and in air conditioning.[20]

Early electronic controllers typically employed a low-voltage a.c. version of the familiar Wheatstone bridge, with the central galvanometer replaced by a voltage amplifier-relay unit (which positioned, say, a valve or damper motor). One of the bridge arms incorporated a sensing element — a temperature change at this element unbalancing the bridge and producing a voltage across the amplifier. The Honeywell system made use of phase-discrimination principles.

Improved reliability and calibration accompanied the introduction of transistorised amplifier units in the early 1960's, and later the use of printed circuit boards.

Other electronic control developments were in the field of electric heat control — first the saturable core reactor, and later the silicon controlled rectifier.

11.12 BUILDING AUTOMATION CENTRES

The sheer cost of fitting individual temperature controls in every room and space in a large building dictates the need for central control. This can be satisfactory as long as there are no severe local load changes; once the installation has been commissioned and regulated, central control should enable the design conditions to be everywhere maintained. But without monitoring, evidence of malfunction can only come via the complaints of the occupants.

With individual room control, the plant operators have little or no control over the room temperature achieved, and so no effective means of avoiding waste of heat. Again, monitoring becomes necessary.

An early example of a monitoring panel is that installed in the Masonic Peace Memorial Building, London, in 1933 (Fig. 11.14). It could monitor some 100 sensors.

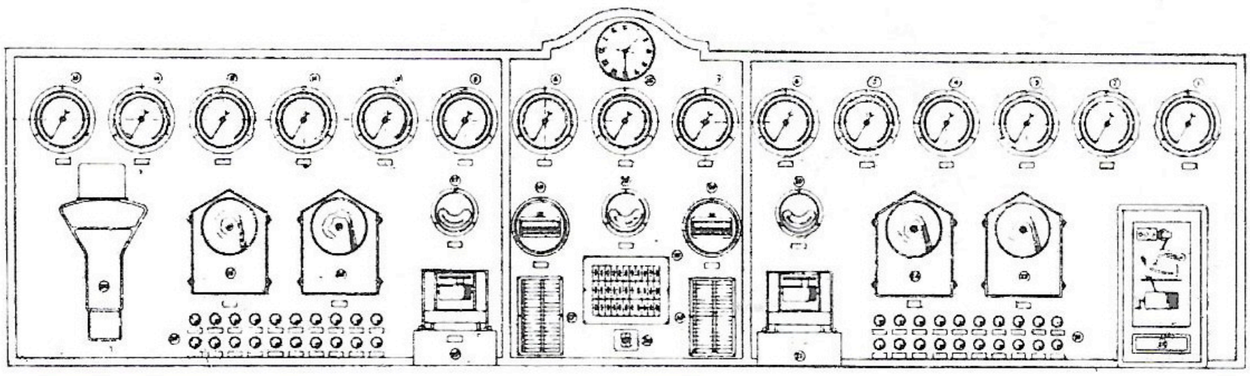

Fig. 11.14. The monitoring panel in the Masonic Peace Memorial Building, London (1933).

Perhaps the most important is that automatic control needs to be monitored so that any failure can be immediately detected. Manual operation ensures this, since the plant engineers will keep an eye on water and air temperatures and on the running of pumps and fans. In complex installations, with numbers of components distributed round the building, this is not possible, save at considerable labour cost.

The modern data centre measures and records temperature and flow at critical points in the system, gives an alarm if they deviate from set limits, monitors the operation of boilers, fans and pumps. A single operator can control the whole installation from a central console. (This is, of course, no more than was done in 1904 at the Budapest Stock Exchange, with the difference that the modern plant is incomparably more complex.)

It is a relatively short step from central monitoring and control by a plant engineer to on-line computer control. This last refinement can be used to optimise the operation of the plant by, for instance, varying flow temperatures or fresh-air volumes to suit the prevailing conditions.

The 33-storey Tennessee Gas Transmission building in Houston had *off-line* computer control provided as part of its building automation system in 1962, while *ca.* 1965 the IMF Building in Washington DC had what was probably the first *on-line* computer controlling its HVAC and lighting services (*Proceedings* HPAC Computer Conference, 1965).

Europe's first computer-controlled air-conditioning system was installed at Paris-Orly Airport in 1971 (*H. & V. Engr.*, April 1972, p. 521). A few buildings spread across the world have had computer control installed not only for the heating and ventilating system, but also for the control of lighting and lifts and for the operation of the security systems.

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