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I.C.T.P., P.O. BOX 586, 34100 TRIESTE, ITALY, CABLE: CENTRATOM TRIESTE

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"Instrumentation and Measurement Methods - Example of Monitored Buildings"

Maurizio ROMANAZZO
ENEA - Cre Casaccia
FARE - INPRO
Rome, Italy

Please note: These are preliminary notes intended for internal distribution only.

INSTRUMENTATON AND MEASUREMENT METHODS - EXAMPLE OF MONITORED BUILDINGS

General Monitoring Criteria

Monitoring low energy or bioclimatic buildings is useful and sometime necessary for the following reasons:

- understand how the new building techonology works both by energetic and dwelling point of view
- validate calculation methods and simulation models

The most important stage of any monitoring project is formulating a good monitoring strategy that articulates in four steps

1) Definition of monitoring objectives : it's a fundamental point choosing which kind of evaluation must be done e.g. heat load,solar contribution (passive, active) comfort level,accurate subsystems analyse etc.

2) Arrangement of an activity program stating :

-detail of experimental analysis e.g. global performance or subsystems perforormance monitoring

-definition of data elaboration criteria (if a simulation model must be valitated matching between monitoring and code requirements is needed)

- Choice of the statistical consistence of data (one season ,one year ,more years measurements)

3) Determination of the variables to be measured specifying if recording must be continuos (short time interval sampling) or spot;the first is the case of most punctual physical variables the other of parameters related to dwelling occupation or users response information.Result of this stage is the drawn up of the list of measuring points.

4) Specification of the instrumentation to be used e.g. sensors and data acquisition system

The monitoring strategy may be different in the case of occupied buildings in comparison with empty dwellings situation : system performance (expecially passive) is strongly affected by the occupants behaviour and measurements must be accepted by tenants.

The planing of monitoring must,therefore,comprise an adequate information action.

The cost of building monitoring is generally high to be neglected therefore it is important to engage instumentation level as simple as possible and measurament period not very long.Thus in one hand it's a big mistake to use a large number of measure points that are unuseful for the subsequent analysis,in the other hand it's wrong not to measure fundamental variables.

May be identified four monitoring levels appropriate for evaluation of different energy saving or solar energy technologies
and different building characteristics.

Level A

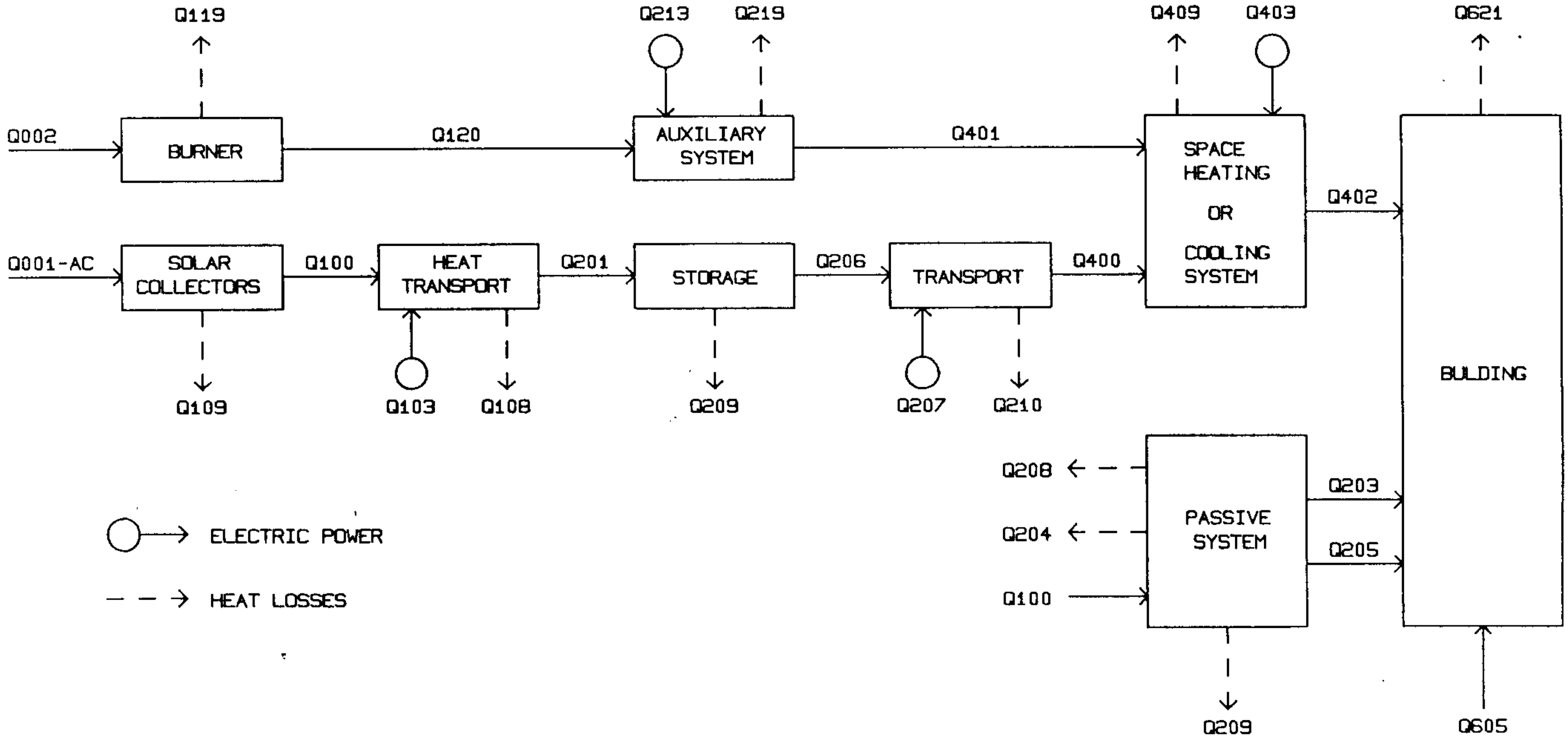
This level is typical of research and development projects relating in most cases to experimental buildings.The instrumentation complexity,the amount of data and the sampling times must be suitable to evaluate the performance of the various componentes of a system and to validate complex simulation models.A detailed determination of energy balances is made and the temperatures distribution is monitored for comfort evaluation.The
measurement points number,for each building, is typically more than 100.

Level B

This level is typical of demonstrative buildings often whith occupant inside.The project is well instrumented to receive answers about the correctness of design criteria adopted,to obtain measured load data and to gain experience in a real situation.To minimize the users pertubation it's necessary to do a relatively small number of measurements in more (5-10) similar dwellings.The measuraments involve heat balance (solar ,auxiliary,heat loss) and average comfort conditions.The number of points measured is approximately 50.

Level C

This level is typical of large scale demonstration programs.The number of measures in each dwelling is very small (some unit) but many dwellings are monitored at same time and are generally obtained statistical data relating to energy saving and comfort levels.The size of the sample eleminaites the uncertainities produced by users behaviour.



Q119
Q213
Q219
Q409
Q403
Q621
Q002
BURNER
Q120
AUXILIARY SYSTEM
Q401
SPACE HEATING OR COOLING SYSTEM
Q402
Q001-AC
SOLAR COLLECTORS
Q100
HEAT TRANSPORT
Q201
STORAGE
Q206
TRANSPORT
Q400
BULDING
Q109
Q103
Q108
Q209
Q207
Q210
Q208
Q204
Q100
PASSIVE SYSTEM
Q203
Q205
Q209
Q605
ELECTRIC POWER
HEAT LOSSES

Definitions

Q001 total solar incident

Q109 heat losses from collectors

Q100 solar energy collected

Q103 operating energy collectors/storage system

Q108 heat losses of collector/storage transport system

Q201 energy supplied by storage

Q202 energy delivered by convective exchange from passive

Q200 variation of stored energy

Q208 overheating intentionally discharged

Q204 heat losses from solar aperture

Q205 uneffective solar energy

Q203 solar energy utilized (passive)

Q605 internal gains

Q621 effective thermal load

Q412 energy supplied by heating system

Q403 operating energy of heating system

Q409 heat losses from heating system

Q402 total energy delivered to building load

Q206 energy from storage

Q207 operating energy of storage/heating system

Q210 heat losses from storage/heating system

Q400 utilized solar energy (active)

Q213 operating energy auxiliary system

Q219 heat losses from auxiliary system

Q119 heat losses from burner

Q401 energy supplied by auxiliary system

Q120 energy supplied by burner

Q209 heat losses from storage

SUBSYSTEM	VARIABLE	DESCRIPTION	DEFINING EQUATION FOR ACTIVE SYSTEM
CLIMATIC	Q001	TOTAL SOLAR INCIDENT	$\int I001\,d\tau$
	N113	AVG. AMBIENT DB TEMPERATURE	$(1/TI)/T001\,d\tau$
ENERGY COLLECT. AND STORAGE (ECSS)	Q100	SOLAR ENERGY COLLECTED	$(1/Ac)\int W100\cdot C100\cdot TD100\,d\tau$
	Q203	TOTAL SOLAR ENERGY UTILIZED	$Q300+Q400+Q500$ or $\int W400\cdot C400\cdot TD401\,d\tau$
	N111	ECSS CONVERSION EFFICIENCY	$\int Q203\,d\tau/Ac\cdot\int Q001\,d\tau$
HOT WATER (HWS)	Q302	HOT WATER LOAD	$\int W301\cdot C301\cdot(TD301+TD302)\,d\tau$
	N300	SOLAR FRACTION OF HW LOAD	$(1/TI)\int[TD301/(TD301+TD302)\,d\tau$
	Q311	ELECTRIC ENERGY SAVED	$Q310-Q309$
	Q313	FOSSIL ENERGY SAVED	$Q312-Q306$
SPACE HEATING (SHS)	Q402	SPACE HEATING LOAD	$\int W600\cdot C600\cdot TD600\,d\tau$
	N400	SOLAR FRACTION OF HEATING LOAD	$\int(Q405+Q406)\,d\tau/\int Q402\,d\tau$ or $\int Q400\,d\tau/\int Q402\,d\tau$
	Q415	ELECTRIC ENERGY SAVED	$Q414-Q413$
	Q417	FOSSIL ENERGY SAVED	$Q416-Q410$
SPACE COOLING (SCS)	Q502	SPACE COOLING LOAD	$\int[W600\cdot C600\cdot TD600+W601\cdot h_{FG}]\,d\tau$
	N500	SOLAR FRACTION OF COOLING LOAD	$\int Q500\,d\tau/\int Q506\,d\tau$
	Q512	ELECTRIC ENERGY SAVED	$Q511-Q510$
	Q514	FOSSIL ENERGY SAVED	$Q513-Q508$
BUILDING/ SYSTEM SUMMARY	N406	AVG. BLDG. DB TEMPERATURE	$(1/TI)/T600\,d\tau$
	Q600	TOTAL AUXILIARY ENERGY	$Q301+Q401+Q501$
	Q601	TOTAL OPERATING ENERGY	$Q102+Q303+Q403+Q404+Q503$
	Q602	TOTAL ENERGY DELIVERED TO BLDG. LOAD	$Q302+Q402+Q502$
	Q603	TOTAL ENERGY CONSUMED	$Q102+Q307+Q411+Q515$
	Q604	TOTAL ELECTRIC ENERGY SAVED	$Q311+Q415+Q512$
	Q605	TOTAL FOSSIL ENERGY SAVED	$Q313+Q417+Q514$
	N601	SOLAR FRACTION OF TOTAL LOAD	$\frac{\int[N300\cdot Q302+N400\cdot Q402+N500\cdot Q502]\,d\tau}{\int(Q302+Q402+Q502)\,d\tau}$
	N602	SYSTEM PERFORMANCE FACTOR	$\frac{\int Q602\,d\tau}{\int[Q306+Q410+Q508+(Q601+Q305+Q409)/NELEC]\,d\tau}$

TABLE 1 PRIMARY PERFORMANCE EVALUATION FACTORS

Level D

Short time measurements for energetic diagnosis of buildings not yet occupied.In this case the number of measures is relatively high but the monitoring period is short(two-three weeks).It's measured internal temperature in more zones and the thermal contributions (solar,fossil,electric).The data are elaborated (also on line) by complex statistical algoritms to determine most important thermal parameters e.g. heat loss coefficient,solar gain,time constant.

The subdivision is a general outline, in the same project may of course be found a mixture of the foregoing instrumentation levels (many dwellings at level C and some at level A or B; before a level D diagnosis and after a level B verification and so on)

Performance Evaluation Procedure

Performance evaluation is mainly based on energy flow analysis of the system "building and heating plants".In fig. is show the thermal flow in a genegal case including solar hot water,space heating and space cooling system using both solar and auxiliary systems,building with passive gains.The analysis is developed by detailed energy balances determination (the detail level is related to the complexity of the programmed monitoring .

For a given subsystem, the amount of energy input must equal the output energy plus the energy losses or the stored energy in the subsystem.The aproach used is to instrument the energy flows except the heat losses (that aren't generally measurable) and to extimate these quantities by the balance equation.

The perfomance evaluation factors can be defined in terms of the heat balances elements, in tab is shown an example of performance evaluation factors definition for active systems (the list is taken from NBSIR 76 -1137).Comfort indexes can also be defined for example calculating the time percentange in which temperature is over or under fixed levels.

Solar Contribution Determination

For solar active systems each flow of energy can be determined basically from the same set of measured data :

- fluid (air or liquid flow) in the thermal circuit
- inlet temperature
- outlet temperature

For active systems supplied with thermal storage average temperature of the storage must also be measured.

For passive technologies the problem is much more complex becouse passive contribution can't be directly measured.The performance of a passive building can be evaluated by the knowledge of the amount of its heating and cooling needs that are met by passive solar.The the determination can be done by forming the building energy balance

Qloss = Qaux + Qint + Qsol +- DQsto

Qloss heat loss by thermal conduction and ventilation

Qaux heat supplied by any active system (oil,gas,solar etc)

Qint heat gains from occupancy and consumpion of appliances

Qsol heat gains from passive building

DQsto change in heat stored by the building

This equation generally presents three unknown quantities :Qloss Qsol DQsto.

DQsto can be easily elimnated using a long period of measurement (much longer than the constant time of the building).Qloss and Qsol can be determined with a regressive analysis of data, setting in a first approximation

Qloss = L(Ti-Te) L heat loss coefficient Ti average internal temperature Te external temperature

Qsol = B*I with B solar aperture and I intensity of solar radiation on the vertical plane ortogonal to south direction

In this way it's possible to extimate the total amount of energy contribution by the sun but it is't generally enough for the following reasons:

-the addition of passive components into the building design affects the heat load of the house (generally increasing it) and we must understand which part of the the thermal gains of the system go to compensate the additional losses

-the solar energy gains are uncontrolled and indipendent of heating requirements,which produces overheat that leads to increase in heat losses and to uncomfortable temperature levels in some hour of the day .Therefore as a consequence of passive solar gains the building heat losses will increase,increasing by the same extent the resulting solar energy contribution.The additional energy needed to mantain temperatures over the set point temperature is not useful and does'nt save conventional fuel.

It's therefore important not to determine the total passive solar contribution but only the "useful solar" energy contribution.It can be done resolving by regressive analysis using the following equation

Qsol.us =(Q saved) = Qref - Qaux - Qint

where Qref = L*(Tref-Test) with Tref reference comfort temperature

If a large number of otherwise similar solar and not solar houses is available it's possible to make a solar energy savings extimation by only measuring auxiliary heat loads and statilically analising the average load differences between the two groups.

Measuring Requirements and Instruments

When energy flow schema is drawn and comfort requiriments are outlined it is quite ease to determine the number and the location of the measusing points needed for the monitoring experience.In Tab 2 is shown the type and peculiarities of the measurements to be done for the most usual subsystems.The list fits level B (demonstrative) monitoring.The total accurancies and sampling times are stated to obtain an error in the evaluation of the most important performance factors less than +- 10% keeping relatively low instrumentation cost.

Tab. 2

	code	range	accuracy	sample time	sensor
CLIMATE					
solar radiation horizontal plane	Q000	0-1.5 kW/mq	3%	<1'	thermopile pyranometer
solar radiation collector plane	Q001	0-1.5 kW/mq	3-5%	<1'	photovoltaic pyranometer
outdoor air humidity	H000	10-100 %	3%	15'	dry/wet bulb capacitive
outdoor air temperature	T000	-20/+50 C	.5	15'	Pt resistance thermistor
wind direction	V001	0-360	15	1'	3 cup propeller
wind speed	V000	0-50 m/s	.5		potentiometer
ACTIVE SOLAR SYSTEM					
inlet air or water teperature	T10x	0-120 C	0.1 C	5'	Pt resistance
outlet temperature	T11x	0-120 C	0.1 C	5'	Pt resistance
fluid flow	W100	variable	2%	1'	range dependent
electric energ for pumps etc.	E10x	variable	2%	1'	electronic wattmeter
AUXILIARY SYSTEM					
inlet air or water temperature	T40x	0-120 C	0.1	1'	Pt resistance
outlet temperature	T41x	0-120	0.1	1'	Pt resistance
air flow	W40x	variable	2%	1'	hot wire turbine
water flow	W41x	variable	2%	1'	range dependent
gasoil flow	W420	variable	2%	1'	turbine
storage temperature	T43x	0-100 C	0.1	15'	Pt resistance

electric energy	E40x	variable	2%	1'	electronic wattmeter
COMFORT					
indoor humidity	H60x	10-100%	3%	15'	dry/wet bulb capacitive
indoor temperature	T60x	0-50 C	0.3	15'	Pt resistance thermistor
mean radiant temperature	T61x	0-50 C	03	15'	temperature in black ball

Building monitoring involves therefore following measures:

temperature

solar radiation

mass flow of gas or liquid

humidity

wind speed and direction

elctric energy

A brief analysis of each type of measure is useful

Temperature

Following temperature measurements are required:

temperature of air (ambient or in ducts)

liquid temperature in piped circuits

solid building elements temperature

surface temperature

For temperature measurement of gas,liquid or solid four types of sensors can be used:

Thermocouples

Resistance temperature devices

thermistors

solid state active devices

Thermocouples consist of two dissimilar metal wires joined at one end.If the junction is placed in the point of temperature mesurement and the free ends are maintained at a known temperature an electromotive force is generated which is related to junction temperature.The relation between voltage and temperature is not linear;typically to achieve 1 degree accuracy a rapresentation with a polynomial of order more than eight is needed.Suitable thermocouple types are Chromel/Alumel,Chromel /Costantana ,Iror/ Costantana,Copper/Costantana.

Main advantages are:selfpowering,inexensiveness,wide range

Main disavantages:non linearity,low voltage,instability,reference requirement

The advantage-divantage mixing makes thermocouple use convenient mainly for high temerature measurement (more than 200 C e.g.burner efficiency etc.)

Resistance Thermometer Devices (RTD)

Sensor response is based on the relationship between changes in temperature and resistance of a metal.

Every metal resistance is related to its temperature but only nickel and platinum are generally used because they have proper characteristics(higher resistence,higher temperature coefficient,

stability,corrosion resistance).Pt resistance is most frequently used because it has highest resistivity (0.098 ohm/mm2*m) and corrosion resistance.Relationship betwenn Pt resistance and temperature is alvo very linear:with a straight line accuracy is 0.3 C otherwise with second order polinomial,if calibration is made,accuracy better than 0.1 C is easily obtainable.

Main advantages of thermoresistance are:stability,accuracy , linearity

Disvantages:more expensive,precise current source required,small resistance change and low absolute resistance

the stability and accuracy make however the Pt resistance the most suitable sensor for low temperature measurements(-20_ 150 C)

Thermistors

The thermistor ,also, is a temperature sensitive resistor ,the material in this case is generally a semiconductor.

Main advantages are :high response,low response time,two wire ohms measurement

Disadvantages:strong non-linearity,unstability

Also if the non-linearity can be dealt with the software of a computerized measurement system,the decalibration that often occurs during the work of the sensor make its use unconvenient.

Solid state devices

Monolithic linear temperature sensors both voltage and current output configuration are available.The typical sensivity is 1 microaampere for C or 10 millivolt for C.Except the fact that they offer a very linear output these sensors have the same disadvantages of thermistors

For surface temperature measurement(collector,solar wall,thermal bridges) two tipes of sensors can be used :

thin film (RTD or termocouple)

infrared non-cotact termometer (pyrometer)

Only non contact sensor guarantees an imperturbed surface temperature measurement,also if pyrometrer measures infrared radiation emission that is strictly related to the surface temperature only if the correct surface emissivity is used and reflection of the emissions of surrounding surfaces are avoided.

Solar Radiation

Solar radiation that reaches ground surface (global irradiance) is composed by radiation that directly comes from the sun and radiation that is scattered by the sky in any direction (diffuse radiation).For level A monitoring both direct and diffuse component must be measured; for B an C level global irradiance is enough.To measure the diffuse component can be used the same type of sensor than for the global irradiance obscuring the sun itself so that only radiation from the sky falls onto the sensor(shaddow band mounting)

For measuring solar radiation two types of sensors are used

thermopiles pyranometer

photovoltaic pyranometer

The first is based on the principle of detecting the temperature difference between black an white surfaces , using thermopiles, exposed to solar radiation;the other is a calibrated photoelectric

cell.Both sensors give generally a low voltage output (millivolts)

Pyranometers are classified by the WMO as class one and two depending upon quality characteristics (sensivity , stability , ,linearity ,temperature error ,time constant, spectral response etc.) thermopile pyranometers must be used if reliable measurement must be done because photovoltaic sensor have generally a response that changes in different sky conditions.

Wind Speed and Direction

Wind speed and direction must be monitored continuosily only in level A monitoring because they affect ventilation rates and heat losses form buildings and from solar collectors.This is not a very critical measurement,therefore for level B or C can be measured for a period or acquired from a local meteorological station.

Two types of sensors are generally used

the 3 cups (speed) and vane (direction) anemometer that is bidirectional

propeller 3 -D anemometer, tridirectional

The first type is less expensive and generally adequate if a wind energy analysis is not needed.

Humidity

The knowledge of the humidity of the air is necessary to determine the real comfort conditions,and specially in the case of air distribution heating systems to calculate correct enthalpy fluxes.

There are many different types of sensor based on various physical properties (more than twenty) ;the most suitable for building monitoring are:

psychometer (wet and dry termometer)

capacitative hygromrter

The first is more accurate but has the disadvantage that the water must be periodically added.

Mass Flow

Mass flow of liquid or air must be measured for any heating system (solar or auxiliary) to determine heat balances.Many types of measuring devices are available both for liquid and air flow measurement.For a proper choose of the meter to be used many elements must be considered :

accuracy

cost

flow range (minimum and maximum value)

caused pressure drop

clean or dirty fluid

available straight duct lenght

One of the following types of flowmeter is generally used :

Turbine flowmeter

A turbine is moved by the fluid passing it , the number of revolutions for unit time , proportional to the fluid speed, can be sensed by an external magnetic pickup.

Turbine flowmeter is sensitive to dirty,therefore can be used only for clean fluids (however a filter must be used).These flowmeters should typically be preceeded by a straight distance of at least ten times the diameter of the pipe.Cheapest turbine flowmeters (generally used for monitoring consumption of domestic water) have accuracy 3-5 % but are not very sensitive to low flows.

This meter can be properly used for oil flow monitoring.

Inductive flowmeters

This meter uses the Faraday effect measuring the voltage induced in an electrically conductive fluid flowing through a magnetic field orthogonal to the direction of flow;the voltage is proportional to mean flow velocity and to the magnetic field intensity.The only restriction for the operation of inductive meters is that the fluid must have a minimum conductivity : water has no problem,oils are excluded.

Inductive flowmeters don't cause pressure drop and don't require any straight piping upstream ; they are very accurate on a wide range (rangeability 10-1 with accuracy 1%) and have generally linear output (0-20 mA , 4-20 mA).Main disadvantage is that they are quite expensive

Pressure differene devices

The operation of this meters is based on the measurement of the pressure drop across the device (obstructive element):the pressure difference is measured using pressure transducers e.g. strain gauge,piezoelectric sensors.The most frequently used pressure difference devices are:

Venturi Tube for liquid (consisting of a conical convergent ,short cylindrical tube and conical divergent section)

Pitot Tube for gas

The pressure difference meters are not linear , have not very large rangeability (3 with accuracy of 2%) but are cheaper than magnetic flowmeters.

Vortex Shedding Devices

These meters consist of a blunt obstrusction with sharp edges; the presence of this structure into the pipe ductwork creates regular vortices whose frequency varies linearly with flow rate (Krnman vortices).The frequency can be sensed by thermal or pressure sensors.These meters have good accuracy (typically 2 %) and reliability.

Hot Wire Meter

This meter is based on the measurement of the heat losses a

s an heated wire placed in a fluid stream.It is found that the difference between the temperature of the wire and the temperature of the fluid is function of the fluid velocity.This sensor is generally used for air flow measurements (hot wire anemometer)

Data Acquisition System

For A and B monitoring levels a large amount of measurement must be done at short time intervals (for example if 50 measurement points are foreseen every minute 72000 values every day must be acquaired).In these case monitoring must be done in encoded form and instrumentation must be controlled by a computerized system e.g an automatic Data Acquisition System (DAS) must be used.

The data acquisition system performs essentially the following functions:

-analog and digital signals collection

-transformation of analog signals to encoded form (AD analog to digital conversion)

-initial data elaboration and reduction e.g. software conditioning of data, mean values and standard deviation calculation, elimina tion of values out of acceptable range etc.

-storage on mass memory support of reducted (or of all) data

-optionally transmission of data (via telephone link) to a centra lized copmputer for the data analysis.

DAS is typycally formed by :

a)Minicoputer (CPU,RAM,ROM,Mass Storage,intrfaces for instrumentation) provided with software for instrumentation control and data reduction

b)Acquisition unit that (governed by the minicomputer) performs the measure channel selection (by the multiplexing circuitry) , analog to digital conversion ,signals conditioning (amplification ,reference current or votage generation for sensors,optical isolation)

In the last years the DAS technology was very much developed so powerful systems to low cost are now available; it means that generally DAS is often a smaller problem, both by functional and cost point of view ,respect to sensors.

Between different DAS architectures the didtribuited one(acquisition unitis are spatially separated and hardware and software linked) fits more to buildings monitoring avoiding expensive and not reliable large wiring.In fact if any sensor is connected to the same acquisition unit copper wires must be laid out to long distances producing:

significant cost for wires and installation work

greater presence of disturbs.