A SIMULATION MODEL APPLIED TO CLIMATIZATION PLANT PERFORMANCE ANALYSIS IN PRESENCE OF THERMAL STORAGE

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ABSTRACT

A comprehensive simulation model, based on the TRNSYS program, for the evaluation of thermal storage system behaviour in building climatization. is presented here. The algorithm is applied to the study of a typical office building in presence of an ice or water storage. Possible economic advantages are presented and analysed. The remarkable differences obtained with different plant options confirm the necessity of an accurate study and justify the use of comprehensive computer models. The results suggest better opportunities with water storages because a water tank can give further economic savings in presence of heat pumps in winter.

INTRODUCTION

The widespread use of time of day electric rates by which electric utility companies wish to encourage large consumers of electricity to reduce their on-peak electric consumption has favored a new interest for daily thermal storage. An appropriate design and a correct plant management can permit a full utilization of the advantages offered by time of day electric rates obtaining an economic saving, sometimes remarkable, for annual costs of electric energy. This management saving can make convenient the introduction of thermal storage in spite of the greater initial investement often necessary. However many concomitant factors cause the economy entity of annual electric charge. A foreseen evaluation is therefore very difficult and it needs a precise knowledge of building-plant system behaviour during the whole year in order to calculate electric energy consumption and peak-load for each hourly band. A comprehensive analysis involves the necessity to use sophisticated simulation methodologies. In this way it is possible, for each application case, the comparison of annual performances obtainable by different technical choices offered by chillers, by various types and sizes of thermal storages available on the market, by different regulation strategies of the plant.

A simulation approach is here presented based on the use of TRNSYS program [1] with suitable modifications and additions. The model is applied to the annual performance analysis of office buildings using real meteorological data collected in Padoa. Referring to Italian time of day rates, a comparison in terms of annual electric charges and an economic analysis of the investement have been developed.

BUILDING MODEL

The arbitrariness of extended generalizations forces the necessity to concentrate the attention to building categories absolutely generalizable. So we have assumed typical design data for an office centre in terms of building structures, utilization and management. Multistoried buildings with continous glass walls have been considered. Different areas have been investigated by varying the number of storeys (1 storey=2400 m^2). In fig. 1 the sketch of the buildings with 3 storeys (7200 m^2) and in table I building structures characteristics are presented. Detailed hourly distributions of lighting and persons and electric internal loads (computers) have been assumed as reported in fig. 2.

Climatization plant works during opening hours: from 8 A.M. to 7 P.M., from Monday to Friday.

In the Northern part of Italy office buildings normally present cooling requirements concentrated in few months, for the most part from June to September. In detail official cooling period is from April 16 to October 14, heating is working in the remaining part of the year. Design internal conditions are 50% for relative humidity and temperature of 20°C in winter and 26°C in summer, 2 vol/h air change. Heating is normally obtained by gas traditional boiler. Cold production for summer condition is made by chiller groups utilizing R22 with pluricylindrical reciprocating compressors and air cooling condensers. Refrigerator performances are evaluated by utilizing curves provided from builders. For each step of the calculation, actual cooling capacity and electric consumptions of the chillers are obtained as functions of load factor and thermal levels at evaporator and condenser.

Building model utilized here has been written by the author and it uses a procedure simpler than that one carried on in type 19 and type 56 subroutines of the original TRNSYS program.

Building thermal behaviours and, in detail, trends of hourly thermal loads are calculated by ASHRAE Transfer Functions method [2], [3], [4]. This method is based on the use of transfer function which permit to calculate heat gains from heat transfer through exterior walls and windows, the cooling load from heat gains and, at last, heat extraction rate and room temperature from the cooling load.

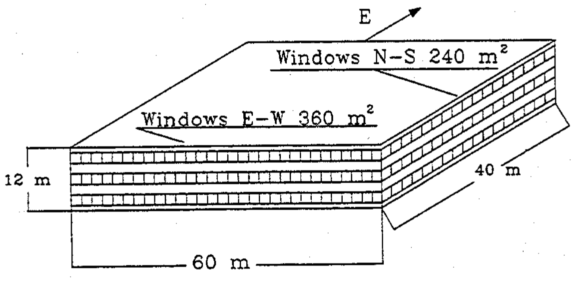

Fig. 1 A sketch of the office centre in the case of 3 storeys building (7,200 m^2).

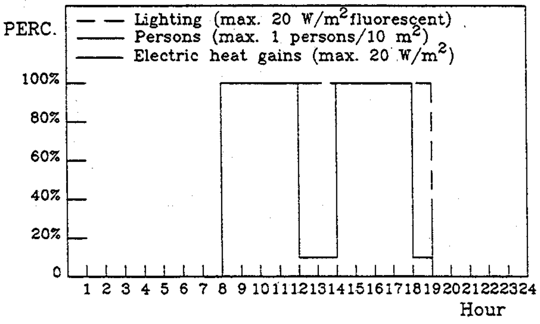

Fig. 2 Daily distributions of lighting, persons and electric heat gains (computer) as percentage of the maximum design values (between brackets).

The coefficients of these functions are available from tables as functions of geometric and thermal characteristics of the room. A generalized use of these values however, can cause approximations and sometimers errors. These errors rise from the difficult to represent by few groups of values all the transfer functions of the numerous building typologies.

In this work transfer function coefficients of the structure, for heat gain estimation, are calculated for the particular walls here considered as, on the other hand, just foreseen in TRNSYS original program.

TABLE I Building structure characteristics.

Descript.	Thickness (m)	Conduct. (W/mK)	Spec.heat (J/kgK)	Density (kg/m^3)
External walls				
glass wall	0.006	1.0	840	2500
polyurethane	0.04	0.035	1600	35
plaster	0.015	0.21	1090	900
Roof				
gravel	0.05	0.70	860	2000
sheat	0.004	0.17	1200	1470
polyurethane	0.03	0.035	1600	35
ferroconcrete	0.05	1.51	1010	2000
Floor				
gravel	0.40	0.70	840	1500
concrete slab	0.15	1.51	1010	2200
sheath	0.004	0.17	1200	1470
light concrete	0.08	0.24	880	800
gres floor	0.05	1.00	800	2300
Windows	K=3.49 W/m^2 K SHC=0.8			

But internal conditions and loads are found following ASHRAE method procedure. However transfer function coefficients to determine cooling load from heat gains and heat extraction rate and room temperature from cooling load are evaluated by a new methodology fully presented in [5]. In fact these coefficients are no more chosen from tables on the basis of a generic room construction feature: light, medium or heavy. Instead they are now calculated, for each case, by means of two parameters: mean thermal trasmissivity and specific mass of the room. Loads and temperature trends, so evaluated, have been tested by NBSLD program [6].

THERMAL STORAGE MODELS

The fundamental comparison between latent heat storages and sensible heat ones has been here simplified, for brevity, to the study of only two types of storage: chilled water tanks or ice in pools. Ice storage has been considered representative of all latent heat storages even if their performances are not really completely coincident. We have studied an indirect storage i.e. a brine solution (a mix of water and ethylene glycol) is circulated between the evaporator and a coil immersed in the tank during nocturnal charging cycle. The ice tank is an open tank and the cooling capacity of the circulating ice water is transferred to the chilled water system via a plate heat exchanger. Because in real system it is very difficult to predict the next day's cooling load, the full charge of the storage is normally always carried out during off-peak hours. Referring to commercial products, easily available on the market, data from builders have been utilized to built up a suitable subroutine to simulate ice storage. Energy balance of inlet and outlet fluxes permits to calculate, at every step of simulation, the storage unit charged fraction. During charging cycle, on the basis of this fraction, experimental curves provide actual storage load to produce ice as a function of inlet brine temperature. The consequent outlet brine temperature and load factor permit to evaluate chiller performances. A complete reloading in 12 hours requests an evaporation temperature about -10°C. This involves a cooling power penalization during charging cycle which can reduce chiller actual capacity until 65%. of the nominal one (when 5°C chilled water is produced).

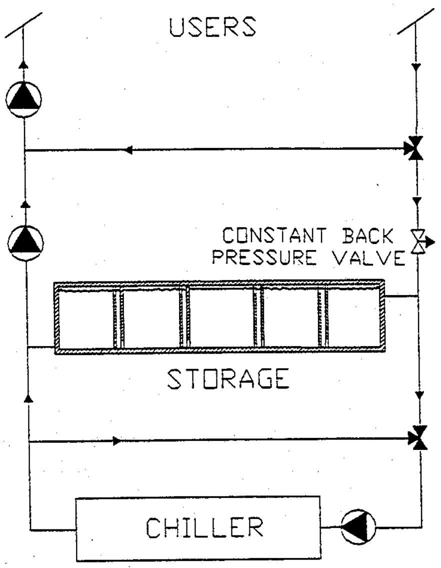

Fig. 3 Sketch of contiguous cells water storage.

For water storages we have supposed the presence of thermal stratification. For a climatization plant which operates with return chilled water temperature of 15°C, a fully stratified storage, starting at 5°C, permits to utilize a thermal rise of 10°C. A complete water stratification is not normally obtainable but by various artifices it is possible to reach a storage efficiency higher than 90% [7]. This efficiency has been considered here as the ratio of total real discharge capacity to maximum theoretical storage capacity in presence of perfect thermal stratification. A multiple cell water storage has been simulated. In fig. 3 you can see its sketch, a series of weirs with horizontal long slot cuts, are present in order to distribute uniformly the introducing and leaving water in the cells. This is very important to reduce the thickness of thermocline i.e. the zone with a temperature gradient between the lighter water on top and the denser water below [7], [8].

Water storage model is based on a modified version of type 4 of the original TRNSYS program. It is characterized by two variable volumes at two different thermal levels (5°C and 15°C) with a thermocline limited to only one cell. Storage efficiency of this cell is estimated equal to 80% [9] e [10]. Heat losses to the surroundings are evaluated for each volume. Since the tank are well insulated, this loss effect is very small.

SUMMER STORAGE

In these application cases where the charging cycle is limited to off-peak hours and daily cooling requirement is remarkable, partial storage is more interesting especially for private users because pay-back periods of the initial investements result normally shorter. Performance comparisons have been developed in terms of annual management cost between no storage plant or in presence of water or ice partial storage. Chiller priority or storage priority can be chosen as control strategy. Storage priority mode requests to establish maximum hourly contribution which can be supplied by storage in order to avoid an early complete discharge.

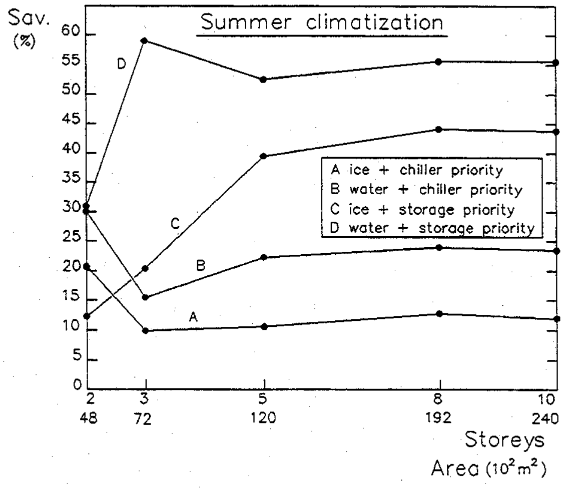

Fig. 4 Percentage savings Sav. (%) with various building areas in the cases studied. These savings are referred to summer climatization electric charge in the case without storage.

A specific analysis [11] has suggested the use of a variable quota equal to a fixed percentage (here 50%) of design cooling load in the same hour.

The design quota, calculated in this way, fixes storage size and chiller nominal capacity. The actual discharging quota can increase in the periods with less cooling needs than design ones but a fully application of this principle requires a difficult prediction of correct next day's cooling load.

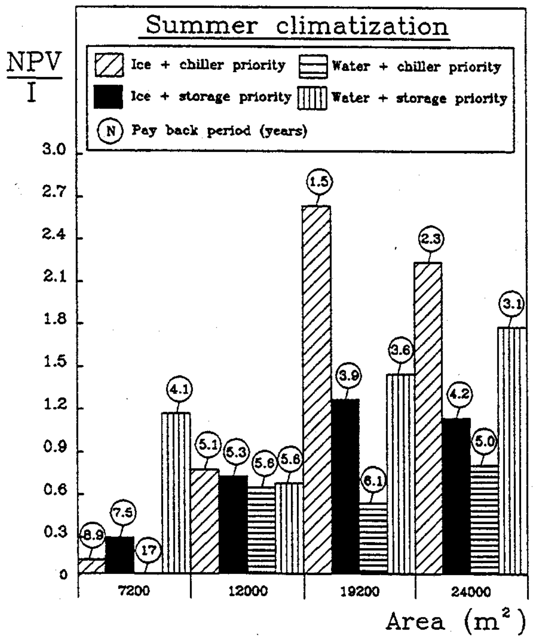

Fig. 5 Return of the investement ROI i.e. ratio Net Present Value NPV to the cost of initial investement I and pay-back periods for various building areas in the cases studied.

In fig. 4 percentage savings on electric charge due to summer climatization referred to the case without storage are reported for various building areas and with different storages and control modes.

The results are strongly influenced by storage and control typology. For the same control mode, water storage gives better economic savings than ice one. This superiority of water storage is probably emphasized by the high cost of electric energy in countries like Italy.

For 2-storeys buildings, we applied simple electric rate, in this case the saving is due only to the reduction of demand cost. But with ice storage this saving is penalized by electric consumption increase connected to the greater electric consumption of the chillers especially with storage priority control when ice production is the greatest.

For 3 storeys building, simulations give an important indication. In fact in Italy time of day electric rates is compulsory when electric peak load is over 400 kW. But in an office building, like this, where electric needs for general use (lighting and computers) during on-peak hours are a remarkable fraction of total consumptions, the use of simple electric rate results cheaper. So with 7200 m^2 area building the introduction of the storage can be particularly convenient because it can permit not to profit from, but to avoid, time of day electric rates reducing peak electric load under 400 kW. This happens with storage priority and in fact we can note a net increment of the economic performances with regard to reference situation without storage which is subjected to time of day electric rates. The advantage is clearer with water storage instead ice storage which is penalized again by stronger electric consumption cost.

From 5-storeys building time of day electric rates are always applied. The results show a scarce influence of scale effect. Best saving are with water storage and storage priority control mode. In this case the savings are over 50%.

An economic comparison developed, in terms of Return of Investement (ROI), i.e. ratio Net Present Value (NPV) to the cost of initial investement, and pay-back evaluations. Net present values (NPV) have been calculated over a period of ten years assuming an actual discount rate equal to 5%. Economic analysis is strongly influenced by the high costs of chiller and storage systems both with ice and water storages. In particular a full cost for underground water storages, expressly built apart from the building, has been considered here. But water storage cost can be reduced if the storage can be placed in a portion of an underground floor or at foundations level of the building.

In spite of the remarkable annual cost percentage savings, pay-back periods result sometimes too long for a real economic interest. This happens with 4,800 m^2 area: with ice storage and chiller priority we have a pay-back period of 8.4 years, in the other cases pay-back periods are greater than 19 years. For wider areas ROI and pay-back periods are reported in fig. 5. For 3-storeys building the possibility to applicate simple electric rate favours water storage with storage priority as just explained above . From 5-storeys, in presence of time of day electric rates, better economic opportunities seems to be first with ice storage and chiller priority and then with water storage and storage priority. Scale effect on cost analysis is normally positive. The differences are however modest. Probably the introduction of suitable predictive algorithms, for a full increase of hourly discharging quota when possible, can become decisive for storage priority convenience.

WINTER STORAGE

The installation of air to water reversible heat pumps instead of simple chillers permits to use water storage also in winter. Now storage works between 50 and 40°C, user circuits between 45 and 40°C. Heat pump starting is controlled by an outside air temperature sensor: when this temperature is below a limit value, heating is provided by traditional gas boiler. Set point limit is calculated, for each electric hourly band, on the basis of minimum coefficient of performance necessary to ensure heat pump working convenience. In off-peak hours, just because the low cost of electric energy, we almost reach the economic equivalence between electric resistors heating and traditional boilers utilization. Maximum heat pump working spur during off-peak hours must be then pursued by correct plant design and control strategies.

In fig. 6 percentage savings obtained in presence of water storage for various building areas are reported. These savings are referred to seasonal cost of heating management if only traditional boilers are used. The possibility to storage thermal energy from heat pump during more favourable daily periods produces effectively remarkable economic savings which can reach about 50% in this application case with Italian electric rates.

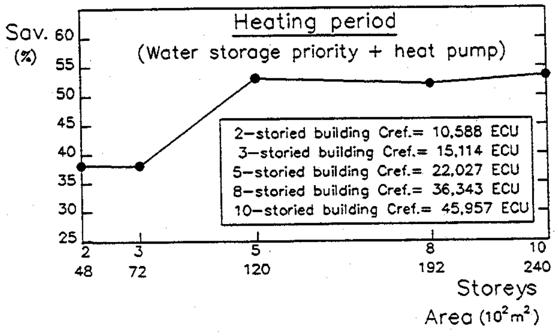

Fig.6 Percentage savings Sav. (%) for various building areas with water storage and heat pumps. These savings are referred to only gas boiler heating cost Cref. (ECU).

You can also note a saving net increment passing from simple electric rate application (2 and 3-storied buildings) to time of day electric rates (from 5 storeys) which permit to take full benefit from storage presence.

In fig. 7 the economic analysis has been presented for the various building areas. Total annual savings about climatization plant management are now considered together with the installation extra costs for reversible machines instead of simple chillers. A water storage working during the whole year results now more interesting and competitive with respect to ice storages.

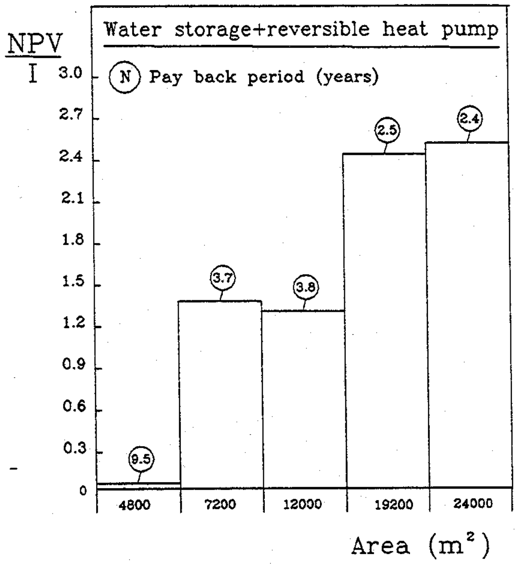

Fig. 7 Return of investement ROI i.e. ratio Net Present value NPV to the cost of initial investement I and pay-back periods for various buildings areas in the cases studied.

CONCLUSIONS

The results show strong differences for energetic but especially economic performances of various design options. Therefore the use of a comprehensive computer model is absolutely necessary for a correct building-plant system behaviour evaluation in each application case.

The molteplicity of causes which determine final economical results makes the generalization of the conclusions very difficult and limited. Even if using great caution, some indications have been however elaborated for these office buildings.

Cold storages permit remarkable percentage savings referred to management cost of air conditioning. But, since the cooling requirement is limited to only a part of the year, the economic evaluation of the initial investement is positive only with greater building areas.

The possibility to use water storage also in winter, as hot storage, clearly improve the economic opportunities of its installation.

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