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Thermal Performance of Concrete Masonry Unit Wall Systems

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ABSTRACT

New materials, modern building wall technologies now available in the building marketplace, and unique, more accurate, methods of thermal analysis of wall systems create an opportunity to design and erect buildings where thermal envelopes that use masonry wall systems can be more efficient. Thermal performance of the six masonry wall systems is analyzed. Most existing masonry systems are modifications of technologies presented in this paper. Finite difference two-dimensional and three-dimensional computer modeling and unique methods of the clear wall and overall thermal analysis were used.

In the design of thermally efficient masonry wall systems is important to know how effectively the insulation material is used and how the insulation shape and its location affect the wall thermal performance. Due to the incorrect shape of the insulation or structural components, hidden thermal shorts cause additional heat losses. In this study, the thermal analysis of the clear wall was enriched with the examination of the thermal properties of the wall details and the study of a quantity defined herein the Thermal Efficiency of the insulation material.

The total wall system thermal performance for a typical single-story ranch house has also been determined. At present, experimental techniques and calculations do not include the effects of building envelope details such as corners, window and door openings, and structural joints with roofs, floors, ceilings, and other walls. Wall details are not sufficiently developed because of the lack of the simple, engineering, analytical, tools to help to estimate the thermal properties of wall details and their influence on the overall wall thermal performance. Current techniques for the evaluation of the wall thermal performance are focused on the thermal resistance value of the clear wall area. The clear wall is a flat, uniform part of the wall, uninterrupted by wall details. Traditionally, only this area is tested and most of the theoretical calculations are provided only for this area. This simplification can lead to errors in determining the energy efficiency of the building envelope. In masonry wall systems, wall details may have different structure than the clear wall area. Also, highly conductive grout, and reinforcement are used very often. These cause additional thermal bridges, which should be incorporated in the thermal performance analysis.

KEYWORDS: BUILDING ENVELOPE, MASONRY, CONCRETE, THERMAL PERFORMANCE

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INTRODUCTION

The large variety of materials available for production of concrete masonry units (CMUs) may enable a more effective design in which concrete units are more thermally efficient. Unfortunately, existing methods to do thermal calculations for building wall systems are based only on the measured or calculated thermal performance of the clear wall area. In this paper, the phrase "clear wall area" is the part of the wall system that is free of thermal anomalies due to building envelope subsystems or thermally unaffected by intersections with other surfaces of the building envelope. The present techniques for quantifying the thermal performance of wall systems have many obvious shortcomings. Building envelope details such as window and door perimeters, wall corners, and floor and ceiling interfaces with the walls along with the additional structural support that these details require, are ignored. As it was discussed in [1] for the cases of the wood and metal frame walls, polystyrene foam wall form system, and two-core CMU wall, these simplifications can lead to errors in determining the energy efficiency of the building envelope.

Clear wall measurements are typically carried out by apparatus such as the one described in ASTM C 236 [2]. A relative large (approximately 8 × 8 ft or larger) cross-section of the clear wall area of the wall system is used to determine its thermal performance. Thermal anomalies, such as concrete webs or core insulation inserts, are typically included in the test configuration. For concrete and masonry walls, building envelope intersections and opening perimeters may represent different construction than the clear wall area. Obviously, the thermal properties measured or calculated for the clear wall area may not adequately represent the total wall system thermal performance. In the past, that fact has often been omitted and, as a result, wall details have not been thermally examined and improved. Investigating areas of possible heat losses in buildings and opportunities to replace highly conductive materials should aid thermal designing of future buildings.

A thermal analysis using a finite difference computer model has been performed on popular masonry walls systems and their details. A finite difference heat conduction code developed at the Oak Ridge National Laboratory (ORNL), was used for thermally analyzing the clear wall areas, corners, opening perimeters, and exterior wall intersections with other building elements [3]. Two-dimensional modeling was used for most of the clear wall areas. For some wall components and for areas where the exterior wall intersects with other building elements, three-dimensional modeling was necessary. The resultant temperature maps were used to calculate average heat fluxes, and the wall system R-values. Using a standard building elevation, these results have been combined to compute the amount of the clear wall area and to determine the overall wall system thermal performance for a typical single-story ranch house. A unique calculating method was used to analyze the thermal efficiency of the insulation material in masonry wall systems.

As shown in Fig. 1, the six following masonry wall systems containing 12-in. (30 cm) wall units were considered during computer modeling:

1. solid block,
2. two-core hollow block,
3. cut-web block,
4. multicore block, and
5. two solid blocks with interlocking insulation inserts.

The thermal resistance for each unit was estimated for five different values of concrete thermal resistivity: 0.19 (1.32) 0.28 (1.94), 0.40 (2.77), 0.59 (4.09), and 0.86 $h \cdot ft^2 \cdot °F/BTU$ per in. (5.96 mK/W). These values approximately correspond, respectively to the following densities of concrete:

- 120 (1,920),
- 100 (1,600),
- 80 (1,280),
- 60 (980), and
- 40 lb/ft^3 (640 kg/m^3).

For each wall system, models of the clear wall area, corner, wall/ceiling (roof/wall) intersection, wall/floor intersection, window header, window sill, window edge, door header, and door edge were analyzed. Geometries of these details were obtained from standard architectural drawings or system manufacturers' design guides [4,5]. Concrete headers Jambs, sills, and heads are normally included in the R-values of the windows or doors. So, they are not taken into account in overall wall analysis. The interaction between the detail and the clear wall area was included in the computations so that the area of the clear wall thermally affected by the subsystem or detail could be derived. The temperatures and wind speeds used in all of the modeling runs were 70°F (21°C) and 0 MPH for the interior space and -20°F (6.6°C) and 15 MPH for the exterior environment.

WALL THERMAL MODELING AND CLEAR WALL R-VALUE CALCULATIONS

Finite difference computer code was used for analyzing the heat transfer in foundation walls, and wall details. It can solve steady-state and/or transient heat conduction problems in one-, two-, or three-dimensional Cartesian, cylindrical, or spherical coordinates [3]. Multiple materials and time- and temperature-dependent thermal conductivity, density, and specific heat can be specified. Two-dimensional modeling was used for most of the clear wall areas. For some elements of wall openings, and for areas of wall intersections with other building structure components, three-dimensional modeling was necessary. Resulting temperature maps were used to calculate average heat fluxes and the wall system R-values.

The accuracy of the predicting of clear wall R-values was confirmed by using 19 published test results for masonry, wood-framed, and metal-stud walls. The phrase "clear wall" was previously defined by Kosny and Desjarlais [1,6] as the flat part of the wall system that is free of thermal anomalies due to building envelope details such as corners, door and window openings, and structural joints with roofs, floors, ceilings and other walls. The comparison between experimental and simulated R-values is presented in Table 1. The 95 percent confidence interval of the Guarded Hot Box Method used for the experiments is reported to be about ±8% [2]. The results of the computer modeling are within this band.

Table 1. Accuracy of HEATING 7.2 R-value calculations.

	Source of information	Number of considered walls	Wall description	Accuracy (%)
1.	R. C. Valore [7]	4	Empty 2-core, 30 cm (12 in.) CMU	3.6
2.	R. C. Valore [7]	6	Filled 2-core, 30 cm (12 in.) CMU	5.6
3.	Martha G. Van Geem [8]	1	Empty 2-core, 30 cm (12 in.) CMU	-0.3
4.	Martha G. Van Geem [8]	1	Filled 2-core, 30 cm (12 in.) CMU	-3.6
5.	Timothy B. James [9]	1	Empty 2-core, 30 cm (12 in.) CMU	-0.9
6.	Timothy B. James [9]	1	Filled 2-core, 30 cm (12 in.) CMU	0.8
7.	Timothy B. James [9]	1	2 × 4 wood framed wall	1.6
8.	W. C. Brown [10] W. R. Strzepek [11]	4	metal stud walls, 40 cm (16 in.) o.c.	5.2

In Table 1, the data presented in the column, "accuracy," were computed based on the following formula:

$$Accuracy = \frac{R_{simul} - R_{test}}{R_{test}} * 100\% \quad (1)$$

THERMAL EFFICIENCY OF INSULATION MATERIAL USAGE

Because thermal insulation inserts are always expensive components of masonry wall units, it is important to effectively use the insulation material. Knowing thermal efficiency (TE) of the use of the insulation material in masonry units can aid in thermal evaluation of existing concrete masonry systems. Knowing how much the insulation material used in the wall affected the walls thermal performance may also be very useful in the design of thermally efficient masonry wall systems containing interstitial insulation.

There are available many masonry technologies containing several types of interstitial insulation inserts. Very often, if the thermal resistance of the insulation used in the concrete masonry unit (CMU) and the increase of the wall R-value caused by this insulation are compered, the actual increase of the wall thermal resistance is much lower than the potential R-value of the used insulation [12]. This is a result of the insulation material being used in an inefficient way so that hidden thermal shorts cause heat losses. The method of estimating its value is based on comparison of the R-values of insulated R_i and uninsulated R_u units each having the same face area F_u. The equivalent R-value of the insulation inserts (R_e) can be calculated for the layer of insulation material having the same face surface area F_u as the CMU under consideration, and containing the same volume V_{ins} which is used to insulate CMU. TE may be expressed by the following equation:

$$TE = \frac{R_i - R_u}{R_e} * 100\% \tag{2}$$

where:

R_i	=	R-value of insulated unit,
R_u	=	R-value of uninsulated unit, and
R_e	=	equivalent R-value of insulation material used.

To get equivalent thickness of insulation d_e, the insulation volume V_{ins} is divided by the face surface area F_u of the CMU. Equivalent thickness d_e can be expressed as follows:

$$d_e = \frac{V_{ins}}{F_u} \tag{3}$$

Equivalent R-value of the consumed insulation material R_e is:

$$R_e = d_e * r_i \tag{4}$$

where :

r_i	=	thermal resistivity of insulation material.

The TE of the insulation material describes the influence of the shape of concrete and insulating parts of the wall unit on the wall R-value.

CLEAR WALL AND OVERALL WALL THERMAL PERFORMANCE

Currently, the evaluation of the wall thermal performance is based on the thermal resistance value of the clear wall area. The clear wall is a flat, uniform part of the wall, uninterrupted by wall details. Traditionally, only this area is tested and most of the theoretical calculations are provided only for this area. Measured or calculated thermal properties of the clear wall area may not adequately depict the total wall system thermal performance. For concrete masonry wall systems, intersections with other building elements, and perimeters of opening are often very different from the clear wall. In the past, this fact has been ignored and omitted in wall thermal analysis. Thermal resistances for the clear-wall and wall details were computed for the following masonry wall systems:

- uninsulated two-core units,
- insulated two-core units,
- insulated cut-web units,
- uninsulated multicore units, and
- insulated multicore units.

For all listed above wall systems, two densities of concrete were considered during modeling:

- for two-core and cut-web units: normal density concrete, 120 lb/ft^3 (1,920 kg/m^3) of thermal resistivity 0.19 h·ft^{2}F/Btu per in. (1.32 mK/W), and
- for multicore units: lightweight concrete, 40 lb/ft^3 (640 kg/m^3) of thermal resistivity 0.90 h·ft^{2}F/Btu per in. (6.24 mK/W).

The influence of wall details on the overall wall thermal performance is different for every structure because of the variety of architectural designs. To allow comparisons, a standard building elevation was used. The standard elevation selected for this purpose is a single-story ranch style house that has been the subject of previous energy efficiency modeling studies [13]. The house has approximately 1,500 ft^2 of living area (55 × 28 ft), 1,328 ft^2 of exterior wall area (elevation), 8 windows, and 2 doors (one door is a glass slider and is included with the windows). The elevation wall area includes 1,146 ft^2 of opaque wall area (an overall wall), 154 ft^2 of windows, and 28 ft^2 of door area. Based on the computed wall detail R-values, the overall wall system R-value was calculated by combining the thermal resistance of the wall details, subsystems, wall intersections, and clear-wall area in a parallel, area-weighted method.

$$R_{ow} = \left[\sum_{i=1}^{i=n} \left(w_i * \frac{1}{R_i} \right) \right]^{-1} \quad (5)$$

where:

R_i	=	R-value of wall component (detail, or clear wall),
i	=	wall component index,
n	=	number of wall components, and
w_i	=	wall component area weighing factor,

where:

$$w_i = \frac{area\ of\ component}{overall\ wall\ area} \qquad (6)$$

The amount of clear wall area was calculated by determining the zone of influence for each wall detail and subtracting that area from the total exterior wall area. The zone of influence was determined by examining the isotherms produced by the modelling runs. The zone of influence was defined as that area where the existence of the detail changed the slope of the isotherm by more than 5°. This slope represents approximately a 1°F change in temperature per inch of length along the wall surface. The area which depicted isotherms that were impacted by the presence of the wall detail was defined as the zone of influence for that detail.

Very often, thermal properties of wall details are different from those of the clear wall area. Distribution of heat losses through the wall details can be different from the wall area distribution. For an ideal wall system, the overall wall R-value should be equal to the clear wall R-value. When the R-value of the details is lower than the clear wall R-value, the thermal performance of these wall details can be improved.

DISCUSSION OF RESULTS

Six types of masonry wall units were considered during computer modeling. For each shape of CMU thermal efficiency of insulation (TE) and clear wall R-value were computed as a function of thermal resistivity of concrete used in block production. A reduction of wall R-value caused by using mortar was discussed as a function of thermal resistivity of block concrete for uninsulated and insulated 2-core units. For uninsulated 2-core units, insulated 2-core units, cut-web units, uninsulated multicore units, and insulated multicore units, a reduction of the wall R-value caused by grout was computed as a function of thermal resistivity of block concrete. Overall wall thermal analysis was performed for uninsulated 2-core units, insulated 2-core units, cut-web units, uninsulated multicore units, and insulated multicore units. Structural drawings of the wall details for solid CMU with the interlocking insulation inserts were not available for the author, so they were not included in the overall wall analysis.

As shown in Figure 2 the thermal efficiency (TE) of the insulation material in two-core, cut-web, and multicore units made of normal density concretes varies from 20-40%. For produced in the U.S. solid units with interlocking insulation inserts - shape B, TE varies from 30-80%, and for produced in Scandinavia shape A units - 70-90%. It can be observed that, if CMUs are made of lightweight concretes, the thermal efficiency of the insulation is higher. It can reach 60-90% for blocks made of lightweight concrete. Insulation in multicore units is very ineffective. For normal density concrete, it is below 20%. The maximum TE value for these multicore units made of lightweight concrete will not likely exceed 65%.

Thermal resistances of six considered shapes of CMUs are depicted in Figure 3 as a function of thermal resistivity of block concrete.

Solid CMUs are normally produced of the lightweight concretes. For such units R-value varies from about 5 to 10 hft²F/Btu (0.8 - 1.7 m²K/W).

As shown in Fig. 3, the thermal performance of **two-core units** made of normal-density concretes is very low; for an uninsulated 12-in. (30-cm) thick unit, the R-value is below 2 h·ft²F/Btu (0.35 m²K/W). Because of this, several companies offer many types of insulation inserts that are supposed to improve the block's thermal properties. Unfortunately, because the inserts are located in air cavities, they cannot eliminate thermal shorts through the transversal concrete webs. For insulated units, the R-value remains below 3.5 h·ft²F/Btu (0.62 m²K/W). If two-core units are made of lightweight concretes (not a common practice in the U.S.), their R-values may be higher - about 4 h·ft²F/Btu (0.7 m²K/W) for uninsulated units, and 8 h·ft²F/Btu (1.4 m²K/W) for insulated units.

Cut-web CMUs were designed to reduced heat losses caused by transversal concrete webs in two-core units. Many types of the insulation inserts for the cut-web units are available in the U.S. market. Even if the concrete web height is radically reduced (about 40% in simulated cut-web units), heat losses still occur through the transversal concrete webs. It can be observed in Figure 3, that the increase of the thermal resistance caused by the reduction of concrete webs is minimal for units made of normal density concretes (comparison of R-value between insulated two-core and cut-web units). For the insulated cut-web unit made of normal density concrete, the R-value is below 5.4 h·ft²F/Btu (0.95 m²K/W). R-values of the cut-web units made of lightweight concrete exceed 11 h·ft²F/Btu (1.94 m²K/W).

As shown in Fig. 3, for **multicore units** made of normal density concretes, the R-value of an uninsulated 12-in. (30-cm) thick unit is below 3.5 h·ft²F/Btu (0.62 m²K/W) and for an insulated unit is about 6.8 h·ft²/Btu (1.2 m²K/W). It is interesting that the R-value of an uninsulated multicore unit is as high as the R-value of an insulated two-core unit. For insulated multicore units made of lightweight concrete, the R-value can exceed 19 h·ft²F/Btu (3.35 m²K/W).

Solid blocks with interlocking insulation inserts are usually made of lightweight concretes. As shown in Fig. 3, for the produced in Scandinavia solid units with integral insulation inserts -shape A, the R-value can exceed 18 h·ft²F/Btu (3.17 m²K/W). For produced in the U.S. shape B unit, R-value can reach 20 h·ft²F/Btu (3.52 m²K/W).

The mortar joint area usually covers 4-10% of the total wall area. Mortar may generate additional wall heat losses in masonry walls. Because of the complicated 3-dimmensial character of the heat transfer in areas of mortar joints the reduction of the wall thermal resistance is seldom incorporated in the R-value calculations. As shown in Fig. 4, the R-value reduction can exceed 12% for two-core units. The mortar effect increases when the thermal resistivity of block concrete increases. A reduction of the influence of the heat losses through the mortar on the wall R-value can be achieved by using less-conductive mortars or decreasing the area of mortar joints. In many CMUs, side mortar is being replaced by the interlocking means to connect adjacent units without the usage of mortar.

Construction of load-bearing walls made of hollow-core blocks requires very often installing additional reinforcement and filling air cores with the grout. For all CMUs, grout effect decreases when the concrete thermal resistivity increases. For the grout of thermal resistivity 0.11 h·ft²F/BTU per in (0.77mK/W), the grout effect was depicted as a function of the block concrete thermal resistivity. It can be observed in Figure 4 that, cut-web units are less sensitive to the grout effect (grout effect varies from 3-7%). For two-core units made of normal density concretes, reduction of the R-value caused by the grout poured into the cores is about 10%. For two-core units made of lightweight concrete, the grout effect is about 5%. For uninsulated multicore CMUs, the grout effect remains in the 6-12% range. The R-value of insulated multicore units is very sensitive to the local thermal bridges caused by cores filled with grout. Reduction of the R-value for these units may reach 30% for normal density concretes and 25% for lightweight concretes.

Walls are not homogeneous thermal barriers made from uniform components. Wall details, such as corners or structural connections between wall and ceiling, behave very differently from the clear wall. At present, the impact of the construction details on the overall wall thermal performance is often overlooked. This simplification can lead to errors in predicting the energy efficiency of building envelopes. Results of the overall wall thermal analysis for uninsulated 2-core units, insulated 2-core units, cut-web units, uninsulated multicore units, and insulated multicore units are summarized in Figure 5. For all considered wall systems, except an uninsulated two-core unit wall, the R-values of the wall details are 20-50% lower than the R-value of the clear wall. For the uninsulated two-core CMU system, the R-value of the clear wall area is so low [1.56 h·ft²F/Btu (0.27 m²K/W)] that the thermal performance of the wall details can actually increase the R-value of the overall wall area. In the cut-web unit wall system, two-core units are commonly used for the wall details. For the cut-web unit wall, the R-value of the clear wall area is about 12% higher than that of the overall wall. For uninsulated multicore units, the clear wall R-value is almost equal to the overall wall R-value. For insulated multicore units, the clear wall R-value is 24% higher than the overall wall system R-value. It was observed that for walls made of cut-web or insulated multicore units, R-values of the three most significant wall details (corner, wall/ceiling, and wall/floor details) are 25-50% lower than the clear wall R-value. The wall/ceiling detail has the most lowering impact on the overall wall R-value.

CONCLUSIONS

A series of 2-D and 3-D computer simulations was performed to analyze the thermal performance of concrete masonry wall systems. Six shapes of CMUs were considered during finite difference computer modeling. The analysis of the thermal properties was performed for a wide range of the block concrete densities (from normal density concretes to lightweight concretes). The following series of conclusion were developed. They may be useful in the future thermal designing of CMU wall systems:

The thermal efficiency (TE) of the insulation material in two-core, cut-web, and multicore units made of normal density concretes varies between 20-40%. This shows that 60-80% of the insulation does not increase the wall R-value. Application of lightweight concretes in production of masonry units may help to increase thermal efficiency of the insulation. TE can reach 90% for blocks made of lightweight concrete. Insulation located in multicore units is very ineffective. For normal density concrete, TE is below 20%, for multicore units made of lightweight concrete - from 50 - 60%. It is significant that air cores in units made of normal density concretes create a very inadequate environment for installing any insulation material. Probably, the best solution for these wall systems is the usage of a rigid foam insulation installed on the surface of the wall. The only exception is the Scandinavian solid unit with the interlocking insulation insert (shape A unit). For this unit, thermal efficiency of the insulation varies from 70-90% for normal density and lightweight concretes. In general, insulation inserts installed in units made of lightweight concretes are much more effective.

R-values of most CMUs produced from normal density concretes are very low. The thermal resistance of 12-in. (30-cm) thick uninsulated two-core units made of normal-density concretes is below 2 h·ft²F/Btu (0.35 m²K/W). For the insulated two-core units, and uninsulated multicore units, it is less than 4 h·ftF/Btu (0.7 m²K/W). For insulated multicore and cut-web units R-value is below 7 h·ft²F/Btu (1.23 m²K/W). When the rigid foam insulation cannot be installed (for example when it is danger of the termite damage), the use of lightweight concretes in CMUs production is the most effective way to improve their thermal performance. R-values for insulated multicore units and solid units with interlocking insulation inserts (shape A and B) may reach 20 $h \cdot ft^2 F/Btu$ (3.5 m^2K/W) if they are produced of lightweight concretes. Lower thermal conductivity of these concretes reduces thermal bridges across the blocks and improves the total thermal performance of units. Unfortunately, this also reduces the load that can be carried by these walls due to the lower compressive strength. However, some of these units can by used as left in place wall forms (in the same way as blocks made of insulating foams), where wall structural integrity is provided by the reinforcement and structural concrete poured into cores.

The mortar joint area usually covers 4-10% of total area of the masonry wall. This generates additional wall heat losses. For two-core units, R-value reduction caused by mortar can reach 12%. Also, in many masonry walls, R-value is compromised by the highly conductive grout in air cores. Construction of load-bearing walls made of hollow-core blocks very often requires installing additional reinforcement and filling air cores with grout. For all CMUs, grout effect decreases along with the increase of the block concrete thermal resistivity. For two-core, cut-web, and uninsulated multicore units grout effect varies between 3-12%. In case of insulated multicore units, where grout fillings simply replace insulation inserts, R-value reduction may reach 30% for normal density concretes and 25% for lightweight concretes.

Building wall systems are a combination of the clear wall area and wall details. They cannot be accurately modeled simply by studying the clear wall area. For the wall systems reported in this study, as much as 25% of the overall wall area was different in construction and thermal performance than the clear wall area. For wall units with insulating inserts, R-values of most of wall details were 20-50% lower than that of the clear wall. A fairly straightforward building elevation was used for this modeling; (wall openings represent only 13% of the floor area). In most residential buildings, the wall area distribution has a smaller percentage of the clear wall area because the contribution of the area of wall openings' details in the overall wall area is much higher. In many residential buildings wall openings represent 20-30% of the floor area. If thermal properties of wall details are not incorporated in R-value calculations, significant errors may appear in determining the energy efficiency of the building envelope. For well-insulated masonry wall systems like insulated multicore units, errors can reach 25% of the clear wall R-value. In addition, current techniques de-emphasize creative energy-efficient design of the wall system details because envelope system designers cannot claim performance benefits due to innovative detailing.

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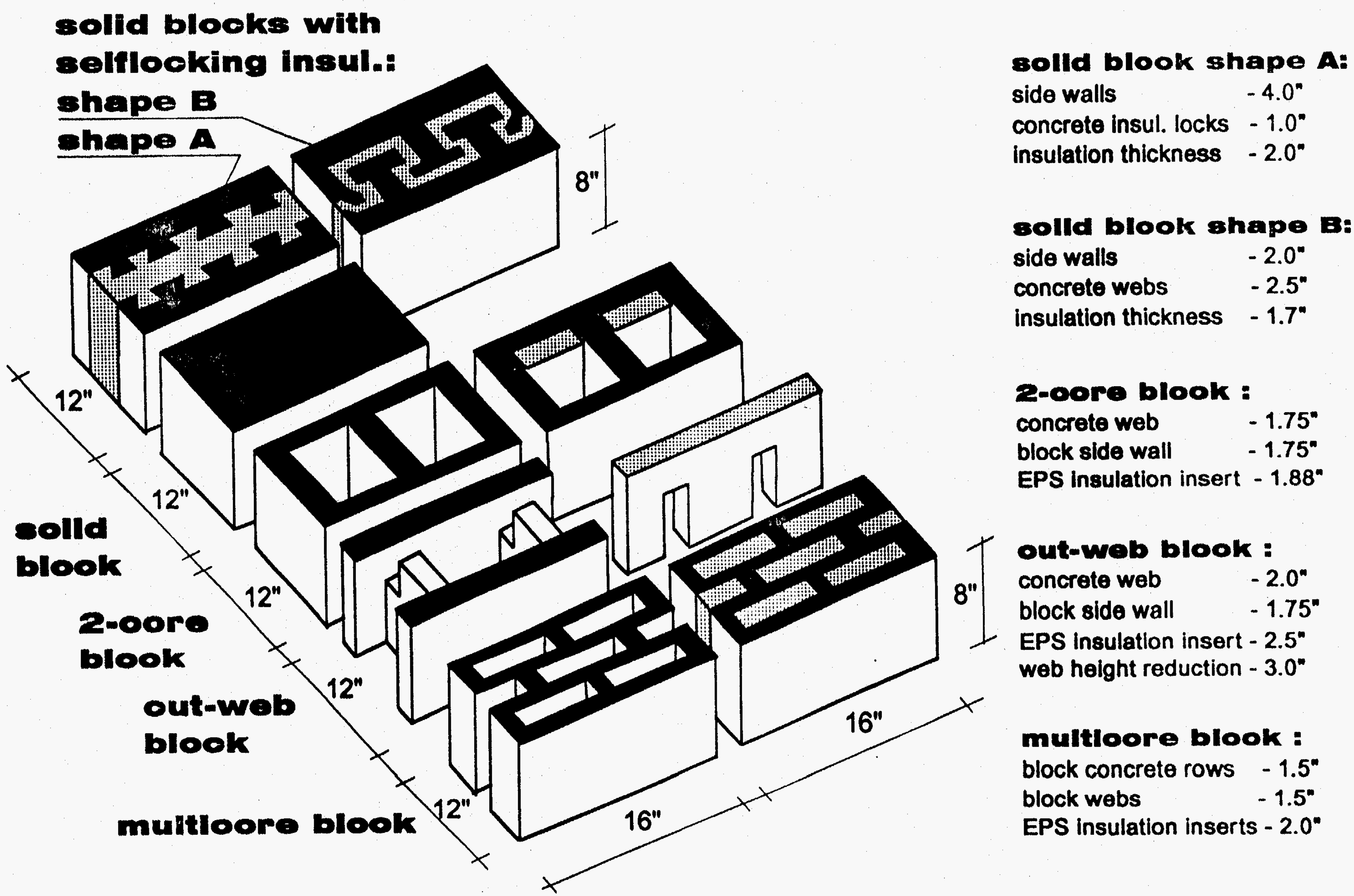

Fig.1. Simulated masonry wall systems.

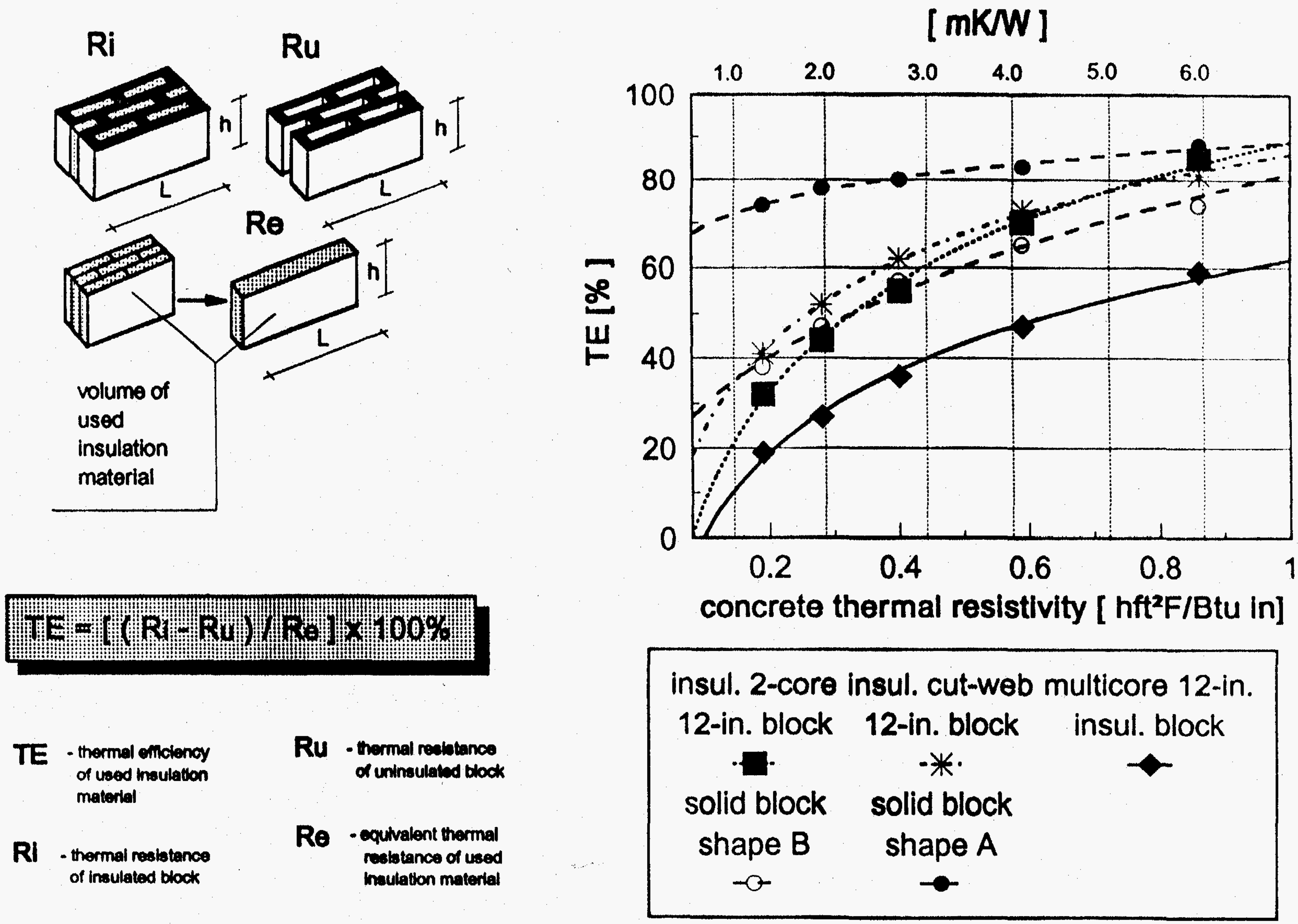

Fig.2. Thermal Efficiency - TE of insulation material in masonry units.

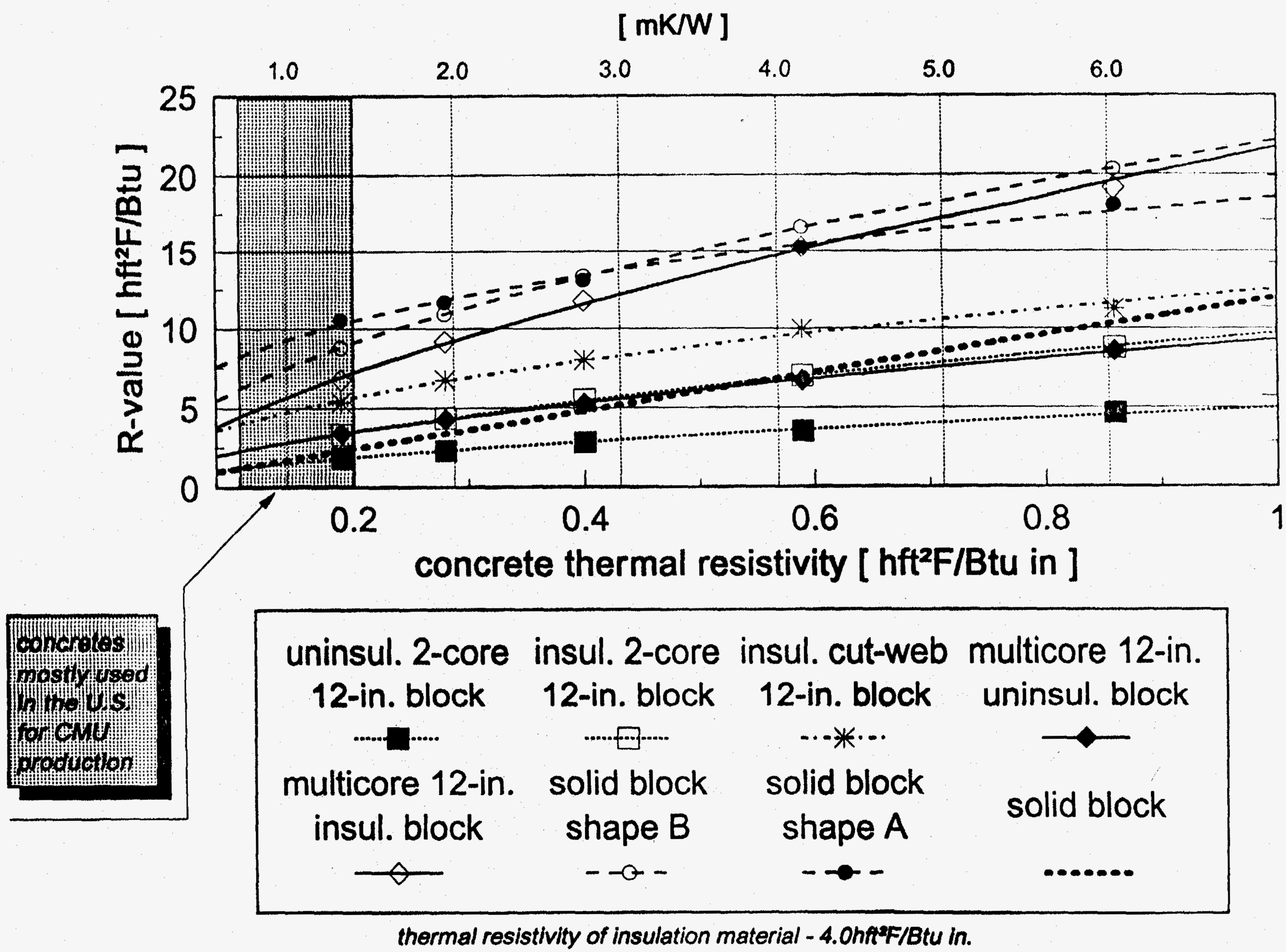

Fig.3. Thermal resistance of masonry units.

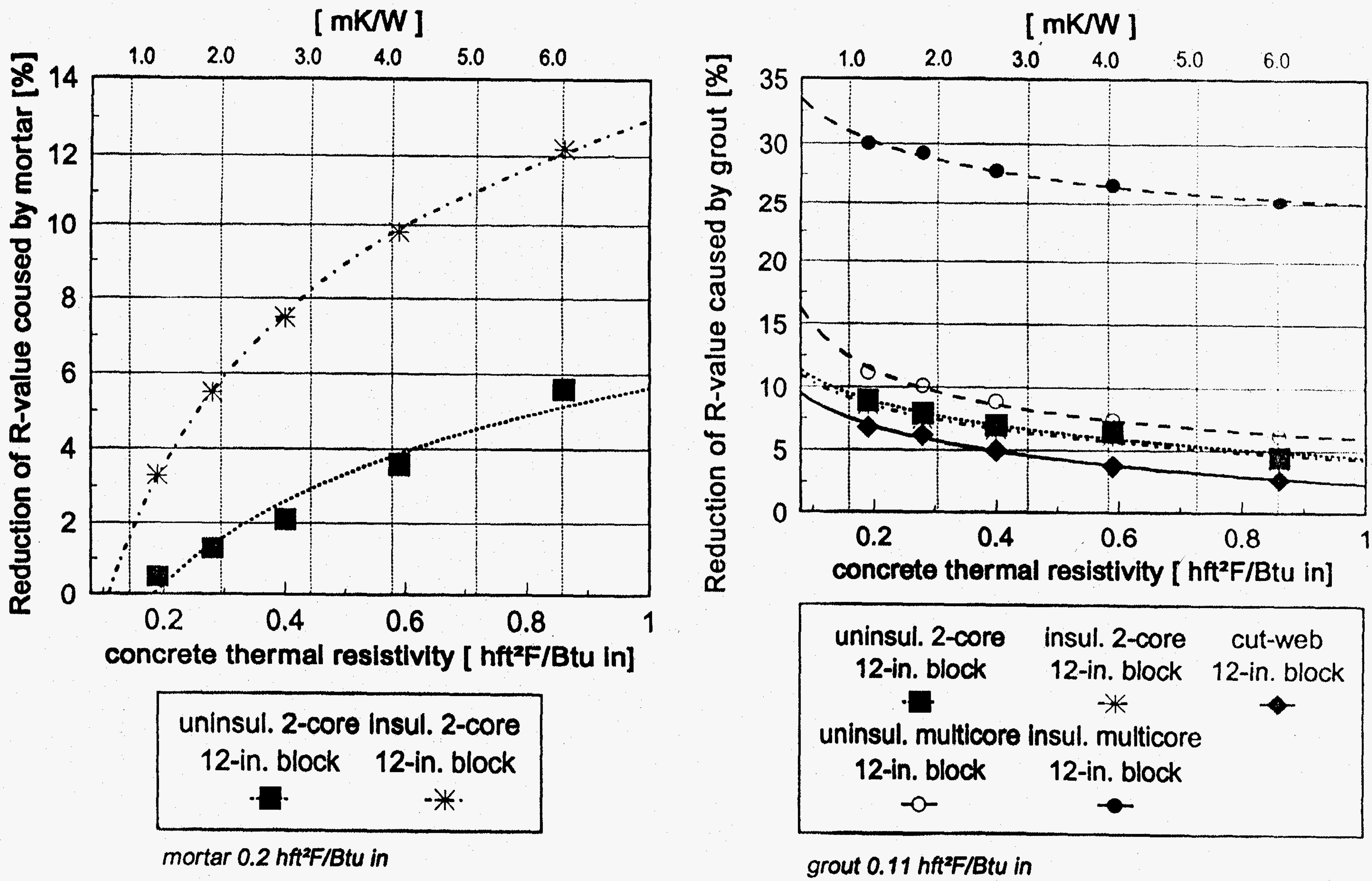

Fig.4. Reduction of wall R-value caused by mortar and concrete poured into cores (grout) in masonry units.

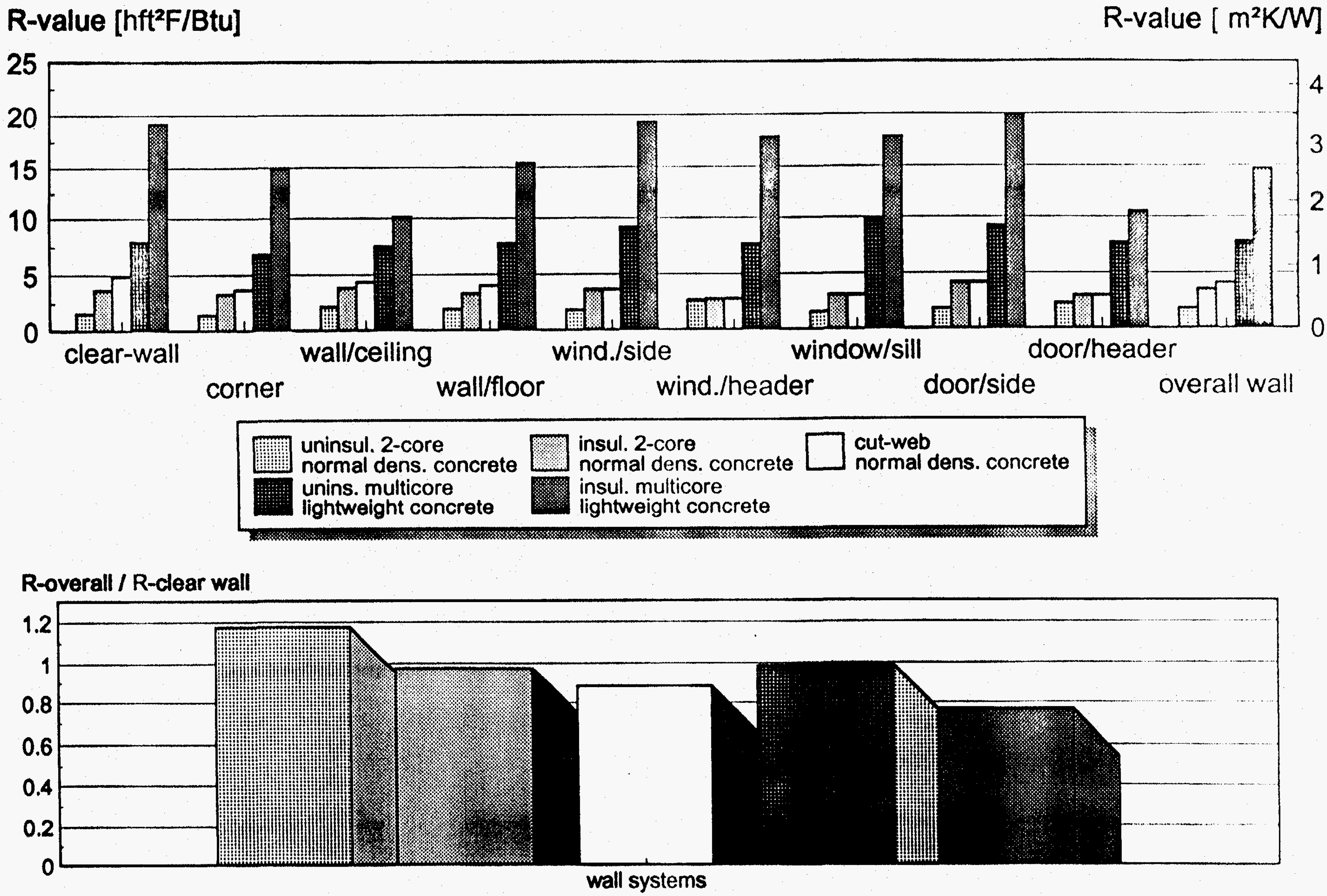

Fig.5. Overall wall thermal analysis for masonry wall systems.