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Natural Convection in the Cavity of a Basement Block Wall

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RÉSUMÉ

Un programme d'expérience en vraie grandeur portant sur les problèmes de soulèvement dû au gel d'un sous-sol isolé est actuellement en cours au Conseil national de recherches du Canada. En plus des données recueillies sur le soulèvement, cette expérience a permis de tirer certaines conclusions intéressantes concernant le convexion naturelle à l'intérieur de la cavité des murs en blocs de béton. Les données expérimentales et un calcul simplifié utilisant la méthode des éléments finis ont tous deux démontré que la convexion naturelle dans un mur de blocs de sous-sol peut constituer un facteur important dans les déperditions calorifiques. La pratique actuelle consistant à n'isoler que la partie supérieure intérieure des murs n'est peut-être pas efficace pour limiter les pertes de chaleur par les murs de blocs, mais l'isolation du mur sur toute la hauteur peut causer une réduction considérable des températures au niveau des semelles.

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SYNOPSIS
A full-scale experimental programme to study the adfreeze/heaving problem of an insulated basement is currently underway at the National Research Council of Canada. Apart from heaving results this experiment has also yielded interesting findings related to the natural convection in concrete-block wall cavities. Both the field data and a simplified finite element model calculation show that natural convection in a block basement wall can be a significant factor contributing to heat losses. Insulating only the inside upper portion of the wall, as is current practice, may not be effective in reducing heat losses with block walls, while full length insulation may lead to significant lowering of ground temperatures near footing levels.

INTRODUCTION
During the last decade energy conservation became an important factor for the construction industry. The problem of heat losses through all components of a building envelope has received considerable attention. A large amount of research work has been done on heat losses from basements, taking into account various types of wall construction, insulation, type of soil surrounding basements, soil moisture content together with soil thermal characteristics and, of course, the effect of climatological conditions [1–7]. The effect of natural convection in the cavity of a block wall has not, however, been sufficiently addressed. This paper examines the overall heat flow through a block wall as well a the consequences of enhanced wall internal cooling by natural convection.

PROBLEM STATEMENT
In accordance with the Canadian National Building Code, basements in all new buildings must be insulated. The vast majority of basements are insulated from the inside, because of the greater cost of placing styrofoam insulation on the outside surface of basement walls, especially in retrofit situations. In order to save energy there has been a tendency to lower the air temperature in buildings in general and in basements in particular. While such conservation measures considerably reduce the heat flow through basement walls, they also cause the zero degree isotherm (frost line) to move further into the wall itself. The interface between the wall and surrounding soil will thus be at a subfreezing temperature, possibly allowing soil to freeze solidly to the wall. If the soil is frost susceptible (clay or silt) and sufficient moisture is available, frost heaving could potentially lift part of the wall. Because typical cast-in-place concrete basement walls have small or negligible tensile strength to resist the shear stress on the wall-soil interface imposed by heaving, the risk

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of damage exists. Concrete-block walls are, of course, even weaker.

In the case of a block wall insulated or partly insulated on its inside surface, there can be a large temperature difference between the inside and outside boundaries of the wall cavity. This temperature difference creates a strong air flow in the wall cavity, which can substantially cool the lower part of the wall by natural convection. The cooling may be sufficient to create conditions favourable for frost heave in the soil near the base of the wall. If, however, the insulation covers only the upper inside wall surface, as is frequently done, heat loss resulting from the enhanced convection may be substantial.

EXPERIMENT

To investigate these potential problems in a field situation an experimental house was constructed on the National Research Council of Canada (NRCC) campus at Ottawa. A complete description of the equipment along with thermal and movement data collected over three seasons will be presented elsewhere [8] and only a short description of the relevant parts of that project will be given here.

All four walls of the experimental basement (dimensions 10 m × 10 m) were constructed with slip joints in the corners to allow independent wall movements (Figure 1). Two of the walls were built of concrete blocks and two of cast-in-place concrete. Both block walls were insulated with 10 cm of styrofoam on the inside surface. One concrete wall and one block wall were insulated full height while the other block wall was insulated only from the top to a level 60 cm below the outside grade. The second concrete wall (facing south) was not used in the experiment. These three walls were instrumented with thermistors for temperature monitoring and with dial gauges for horizontal and vertical displacement measurements (see Figure 1). Thermistors were backed up by thermocouples at selected critical points. Ground temperatures and vertical soil movements next to the wall were measured, and apparatus for periodic *in-situ* monitoring of thermal properties and moisture contents were also installed. Thermistor outputs were automatically recorded at 4 h intervals using a DEC 11-34 minicomputer, while dial gauges were periodically read manually for possible vertical (heave) and horizontal (cave-in) movements.

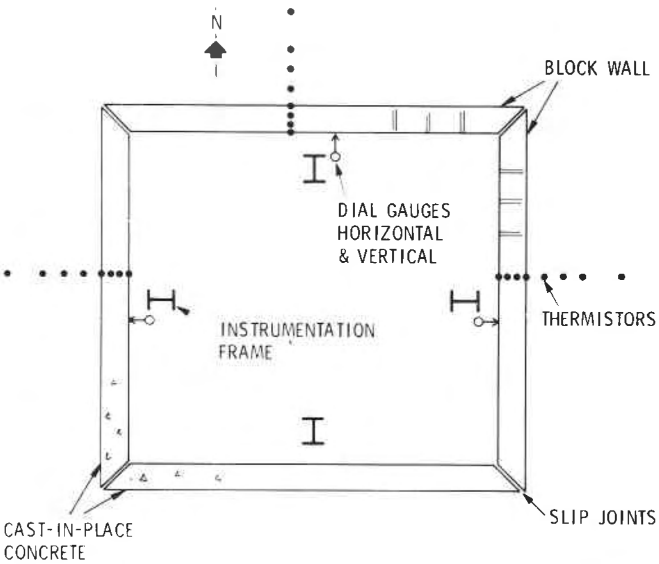

Figure 1 Plan view of the experimental basement.

Experimental Results. Typical early morning mid-winter temperature distributions in the two block walls and the concrete wall are shown in Figure 2. A significant difference can be seen between partly and fully insulated block walls, where the 0°C isotherm in the partly insulated wall is considerably nearer the ground surface, presumably because of the large heat losses caused by natural convection. The temperature difference between the inside of the lower part of the uninsulated wall (+13.5°C at A, Figure 2) and the upper exposed part of the wall (−13°C at B) creates a strong convective cell within the wall cavity. The 0°C isotherm in the fully insulated block wall is at approximately the same location as in the fully insulated concrete wall. This location is largely conditioned by the temperature of the surrounding soil. The temperatures at the base of the walls are, however, distinctly different. The cause of this is again, presumably, natural convection in the block wall cavity.

For the concrete wall, exterior base temperatures are similar to or just slightly warmer than ambient soil temperatures at the same level. Base temperatures for the partly insulated block wall are approximately 3°C warmer than ambient conditions and are the warmest of the three cases. Exterior temperatures at the base of the fully insulated block wall are, by contrast, about 3°C colder than the ambient soil temperatures.

Typical thermal behaviour of the walls with time is indicated in Figures 3 and 4. Temperatures at a similar elevation (approximately 30 cm below ground level) on both inside and outside faces of the concrete are shown versus time for the three wall configurations. Figure 3 presents the cooling trend, and Figure 4 the warming trend. The temperature difference between the two wall surfaces for the block wall remains roughly constant (2 ~ 2.5°C) throughout the winter. This

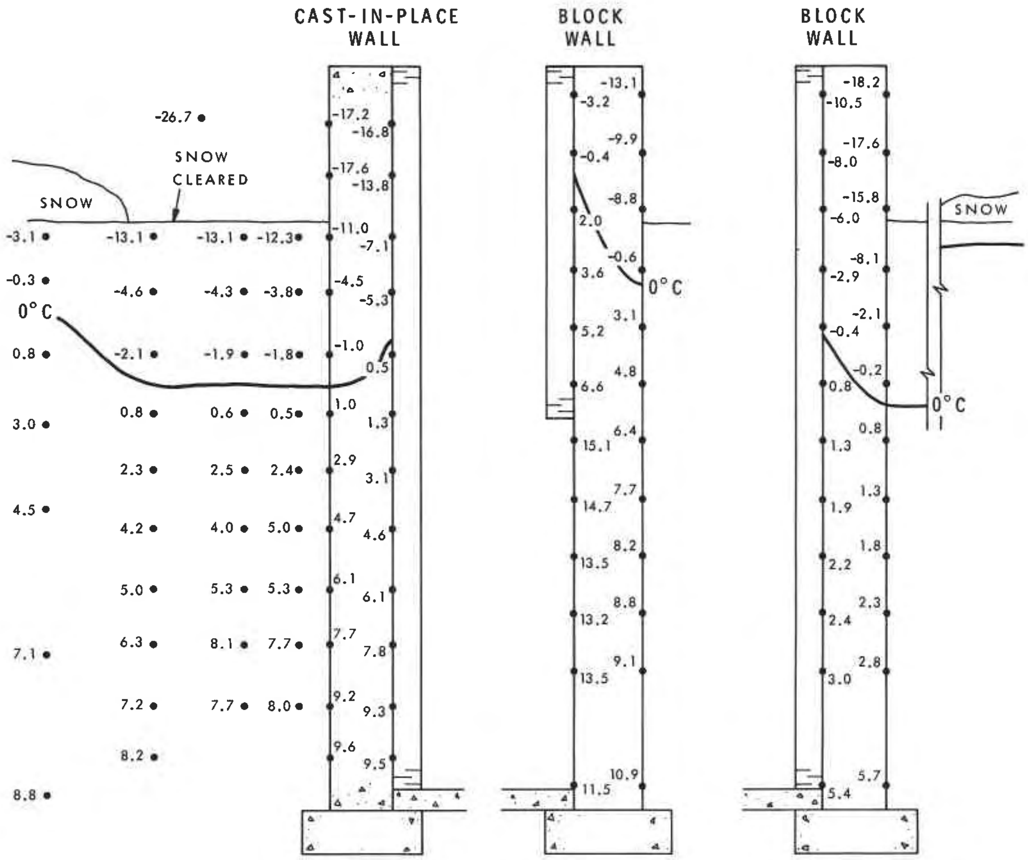

Figure 2
Temperature distribution and 0°C isotherm in basement walls and surrounding ground on January 12, 1984.

is in sharp contrast with the situation in the concrete wall where horizontal temperature differences, far from remaining near constant, even showed reversal on two occasions. In spite of the varying ambient conditions, the temperature differences at similar levels in the two block walls remained nearly constant. This behaviour is further evidence of the important convective transfer occurring in these cases.

FINITE ELEMENT MODEL

A general purpose, finite element program for studying natural convection phenomena developed by Gartling [9] has been used in this work. The following assumptions are implemented in this model: only buoyancy-induced motion and heat transfer are considered in the block wall cavity, while conductive heat transfer alone is assumed in all solid materials. Air in the block cavity is assumed to be a Newtonian and incompressible fluid, the flow to be two-dimensional and laminar, and viscous dissipation to be negligible. The following system of equations was used:

Conservation of Mass: $\frac{\partial u_i}{\partial x_i} = 0$

Conservation of Momentum: $\rho \frac{\partial u_i}{\partial t} = \frac{\partial \tau_{ij}}{\partial x_j} + \rho g$

Conservation of Energy: $\rho c \frac{\partial T}{\partial t} = - \frac{\partial q_i}{\partial x_i} + Q$

Constitutive Relations:

$$\tau_{ij} = P\delta_{ij} + \mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)$$

$$q_i = - k \frac{\partial T}{\partial x_i}$$

$$\rho = \rho_o [1 - \beta(T - T_o)]$$

where u is the velocity vector, τ the time, P the pressure, T the temperature, ρ the density, τ_{ij} the stress tensor, q the heat flux vector, Q the volumetric heat source, μ the viscosity, c the specific heat, k the thermal conductivity, and β the coefficient of volume expansion.

The computer program was developed using the Galerkin method to form the corresponding discretization. Formulation of the program is based on isoparametric elements. This program makes use of either the Newton-Raphson procedure or the Picard algorithm as iteration procedure during equation solution. The frontal method is employed for solution of the matrix equations. Depending on the type of problem under consideration the program can handle isothermal, weakly coupled convection or

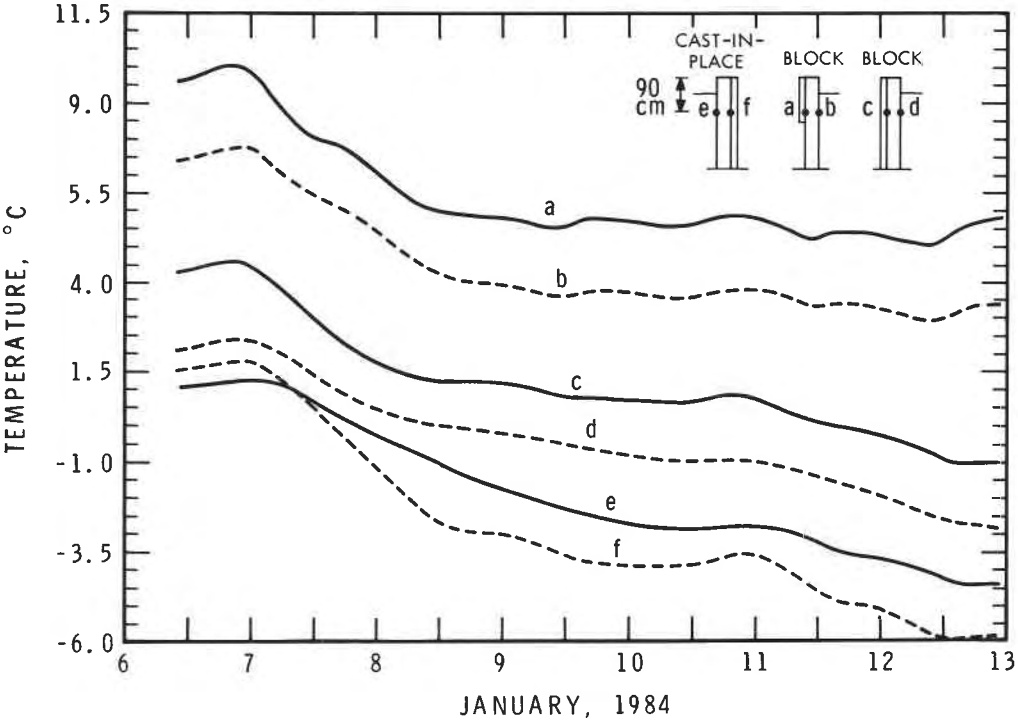

Figure 3
Temperatures of wall surfaces during cooling trend.

strongly coupled convection. The details of the program and finite element methodology employed are described fully in [9].

Finite Element Results. The purpose of the finite element analysis was to show the main trend in the temperature distribution as well as the behaviour of the air flow (streamlines) in the block wall cavity. The objective was not to validate the computer model but rather to compare predicted temperature distributions in a qualitative sense with those measured in the field and, to gain an insight into air movement in the wall cavity.

The finite element mesh consisted of 111 8-noded quadratic isoparametric elements. The

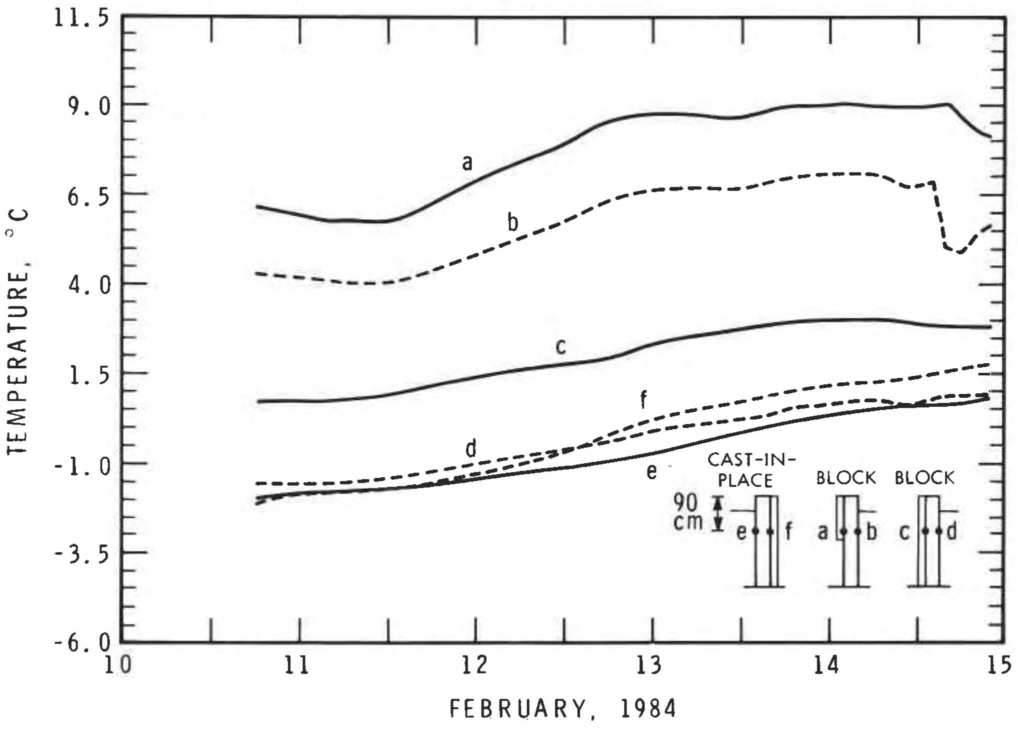

Figure 4
Temperatures of wall surfaces during warming trend.

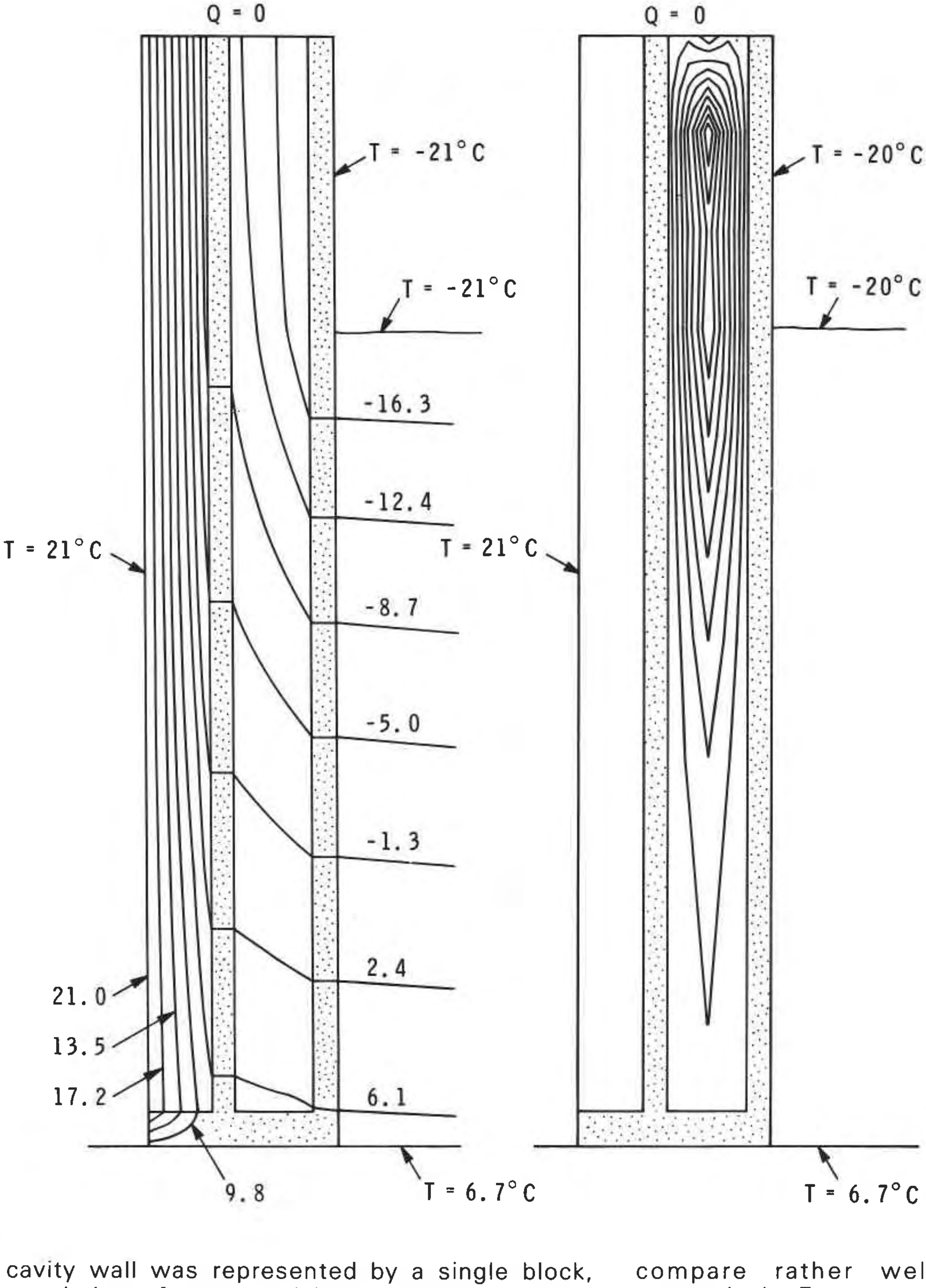

Figure 5
Results of finite element modelling in steady state; *left* temperature isotherms in a basement block wall; *right* streamlines in the block wall cavity.

cavity wall was represented by a single block, consisting of outer and inner vertical concrete members containing an air-filled cavity. The concrete members were modelled as single solid elements whereas the block wall cavity was modelled by a 4 × 11 element mesh.

Boundary conditions used in the steady-state analysis together with computed temperature isotherms are shown in Figure 5a, while air-flow streamlines are presented in Figure 5b. Calculated temperatures are similar to those measured in the experiment. Temperatures on the outside of the wall at the foundation level compare rather well; 6.1°C and 5.7°C, respectively. Form as well as location of most of the isotherms are also similar. An exception is the 0°C isotherm, which, in the field, is located higher than predicted. This is due to the strong influence of latent heat in the soil (not considered in the model) as well as to the transient nature of the actual field situation.

Figure 5b shows the convective cell in the block wall cavity. It is interesting to observe that within the main convective cell spanning the entire cavity two smaller secondary convective cells developed. This is probably caused by the distinct difference in outside wall temperature between the upper exposed surface and the lower buried portion.

CONCLUSION

As a result of this study, certain important, as well as practical, conclusions can be drawn. If basement walls are constructed using concrete blocks, then any opportunity for natural convection to develop in the wall cavity will significantly increase the overall heat losses. With fully insulated block walls, considerable cooling can occur near the base of the wall, which raises the possibility of causing frost heave damage to the footings in appropriate circumstances. Therefore, if insulation is extended right down to the basement floor, it is imperative that the natural convection in the wall be prevented or, at least, significantly retarded. Insulation covering only the upper inside surface may result in high heat losses owing to the enhanced convection made possible by this configuration.

It can be inferred as well that exterior placement of the insulation would reduce temperature gradients and hence convection within the wall cavity. Heat losses would be correspondingly diminished while, at the same time, footing temperatures would not be lowered by the presence of the insulation.

These and other questions arising out of this work will continue to be examined in the future.

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