Proceedings World Geothermal Congress 2000
Kyushu - Tohoku, Japan, May 28 - June 10, 2000

AIR-GAP THERMAL INSULATION FOR LARGE GEOTHERMAL PIPELINES

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Keywords: air-gap insulation, geothermal, large pipeline, pipe insulation, thermal insulation.

ABSTRACT

A single layer air-gap thermal insulation model with atmospheric-pressure air between horizontal concentric pipes was studied experimentally. The inner pipe was an isothermal large diameter geothermal steam pipeline, and the gap/ diameter ratios were small. The outer aluminium cylinder was convectively cooled by the atmospheric air.

Dimensional analysis showed that a transition regime existed in the air-gap model. In this region, heat transfer changed from pseudo conduction to a fully developed laminar convection. The transition region identified was larger than that categorized by previous investigators. It was found that large diameter annuli (i.e. small radius of curvature) led to high Rayleigh numbers that defined the different regimes, while small gap/diameter ratios resulted in lower Rayleigh numbers. The air-gap insulation for geothermal pipelines would be mainly in the transition region. The existing correlations were invalid either because they were based on the fully developed convection or the definition of the regimes was different to what was found in this study.

Four regional correlations were established for determining the Nusselt number in each of the specified regimes. By using these correlations, heat losses can be predicted for the single-layer air-gap insulation.

The heat transfer regimes identified in this study are of theoretical importance and substantiate experimentally the hypothesis predicted by some previous investigators.

1. INTRODUCTION

The main steam transmission pipelines of a geothermal power station can total 50 km long and worth tens of millions of dollars. They generally have a large diameter (>500 mm) with relative low pressure steam inside (<10 bar gauge). The steam pipelines are normally insulated by calcium silicate, fibreglass, or rockwool insulating material and clad by a thin aluminum sheet. The long steam pipelines with a high cost of thermal insulating materials led to the investigation of the use of air as an insulation because of the expected cost advantage, simplicity and benign construction materials. It is known that only one air-gap insulation system is currently being used for large geothermal steam pipelines in Indonesia. However, the design results were not in good agreement with the actual heat losses.

It is of engineering importance that how much natural convection in the air gap of concentric annular will degrade the insulation effect. The solution is very dependent on the shape and orientation of the air gap as well as the boundary conditions. Although many experimental studies have been done in this field, the correlations published are found to have limited validity for certain geometry, flow regime and boundary conditions. There are two important differences between the previous experimental studies and the situation in the geothermal application. Firstly, the ratios of air gap to inner cylinder diameter are much smaller in the geothermal application than those studied previously. Secondly, the outer cylinder is convectively cooled in the geothermal steamfield but previous studies were all based on the controlled isothermal outer cylinder. Theoretically, they are not the same heat transfer problem. Hence existing correlations may be invalid for the design of air-gap insulation for geothermal pipelines.

In practice, the following technical issues using air-gap insulation for the large diameter geothermal pipelines need to be answered:

- What factors influence the heat transfer process?
- How to determine the heat loss from the air-gap insulation?
- What kind of air-gap insulation design should be used?
- How to determine the optimum air-gap insulation thickness?

It is obvious that more research is needed in this field.

2. EXPERIMENTS AND RESULTS

2.1 Steamfield Tests

The steamfield tests mainly involved the measurement of the temperatures of the outside surfaces of the claddings. This enabled the heat losses from the steam pipeline across the air gap to be calculated. These data were also useful for further analysis using dimensionless parameters and for optimum air gap determination. Relevant data about the pipeline on which the tests were carried out in the Wairakei steamfield are summarized below:

Steam transmission pipeline:

Outer diameter of the steam pipe:	762 mm
Pipe wall thickness:	12.7 mm
Steam pressure range:	4 - 5.5 bar gauge
Assumed thermal conductivity of pipe steel:	45 W/mK

The original field test rig was designed as a final year engineering project by Bydder and Hutton in 1997. They constructed two aluminum cladding sections (for 10 mm and 30 mm air gaps), made of 1m long and 0.9 mm thick aluminum sheets. When placed around a steam pipeline they formed a horizontal concentric annular cavity with both ends supported and sealed by endcaps as shown in Fig.1.

Using the same test rig and with some modifications, three sets of tests in Wairakei steamfield were carried out between March and May 1999.

A large tarpaulin (6m×8m) was used as a tent to reduce the effects of wind and rain. The outer cladding temperatures of six gap sizes (10 mm, 20 mm, 30 mm, 40 mm, 50 mm and 75 mm) were measured for the single-layer air-gap model (Fig.2). In addition, the configuration of horizontal coplanar baffles (Fig. 3 (a)) was also investigated for the 30 mm gap. A double-layer gap model (10 mm + 20 mm) was also tested using the existing 10 mm and 30 mm claddings (Fig. 3 (b)).

2.2 Field Test Results

2.2.1 Single-layer Air-gap Model

The field test results of the single-layer air-gap model are illustrated in Fig.4. They are presented in terms of convection and radiation components as well as the total heat losses across the air gap for a 1.2 m long annulus of different air-gap sizes. The different modes of heat transfer are related by the following equations:

$$Q_{total,out} = Q_{conv,out} + Q_{rad,out} \qquad (1)$$

$$Q_{total,out} = Q_{conv,gap} + Q_{rad,gap} \qquad (2)$$

where

$Q_{total,out}$ = total heat loss across air-gap [W],
$Q_{conv,out}$ = natural convection from the outside surface of outer cylinder (aluminum cladding) [W], by Churchill and Chu (1974) correlation,
$Q_{rad,out}$ = radiative heat loss from aluminum cladding to environment [W],
$Q_{conv,gap}$ = convective heat transfer inside the air-gap [W],
$Q_{rad,gap}$ = radiative heat transfer inside the air-gap [W].

$Q_{rad,gap}$ is determined by the energy balance method for the thermal radiation in an enclosure formed by two long concentric cylinders (Mills 1995). $Q_{rad,out}$ can also be calculated using a special form of an equation applied for the situation of a small object in a large, nearly black surrounding. In addition, pure conduction inside the air gap ($Q_{pure,cond}$) was also calculated for comparison in Fig.4.

Fig.4 shows that the minimum total heat loss occurs at 30 mm air gap (for steam pipe OD = 762 mm) and the maximum total heat loss happens at 10 mm air gap. The total heat loss will decrease if the air gap increases from 10 mm to 30 mm. After that, increasing air gap results in more heat loss until the gap reaches 50 mm, after which the total heat loss approaches a constant value. The pure conduction curve ($Q_{pure,cond}$) intersects the convection (inside the gap) curve ($Q_{conv,gap}$) at 10 mm gap size, indicating that pseudo conduction occurs when the gap size is less than 10 mm. The difference between these two curves gives the contribution of the convection in the annulus.

2.2.2 Baffled and Double-layer Gap Models

The results of the preliminary investigation of the baffled air gap as well as the double-layer air gap (see Fig. 3) are shown in Table 1. The results of the 30 mm single-layer air-gap (none baffle) is also given in the table for comparison. Note that the heat losses in Table 1 are for 1.2 m length of pipe.

Comparing to single layer air gap, the results show that using two horizontal coplanar baffles in the annulus decreases the total heat loss by 8%, while the double-layer air gap reduces the heat loss by 41% (pipe temperature was lower but ambient temperature was also lower). Hence, it is experimentally proven that the baffles inside the air gap can hinder the air from convecting and result in a lower heat loss across the air gap. The lower cladding temperature of the double-layer gap model is also attractive from safety point of view.

3. ANALYSIS AND DISCUSSION

In order to identify the heat transfer regimes and to find useful correlations for heat loss calculation across air gap, analysis using dimensionless parameters as well as comparison with various correlations were carried out. The dimensionless parameters used are average Nusselt number (Nu_δ) and Rayleigh number (Ra_δ), which are all based on the air-gap thickness (δ). Five existing correlations chosen for comparison with the test results are:

- Raithby and Holland (R&H) correlation (1975)
- Kuehn and Goldstein (K&G) correlation (1980)
- Buchberg and Catton (B&C) correlation (1974)
- Yunus Çengel's (Yunus) correlation (1997)[1]
- VDI correlation (1991)[2]

Fig.5 shows the average Nusselt number versus the Rayleigh number using log-log plot for the test results in comparison with the five existing correlations. The field test results do not give a straight line in the log-log plot, implying that our heat transfer problem of large geothermal pipe cannot be correlated by a simple power law. In contrast, the existing correlations on the steady state free convection are all straight lines except Kuehn & Goldstein correlation which considers a transition region where heat transfer regime changes from conduction to convection. It is also seen that the field test curve has a similar trend to the Kuehn & Goldstein correlation, and both Nusselt numbers approach unity (Nu_δ = 1) when Rayleigh number is 2.3×10^3 (corresponding to 10 mm air gap). Based on heat transfer theory, Nu =1 indicates that only conduction occurs at 10 mm gap. This implies that there exist a pseudo conduction region when $Ra_\delta < 2.3\times10^3$. This is almost in agreement with Grigull and Haufs (1966) categorization of flow patterns where a pseudo conductive regime is defined as $Ga_\delta < 2.4\times10^3$ (i.e. $Ra_\delta < 1.7\times10^3$ for air).

Observing the trend of the field test curve for $Ra_\delta > 5\times10^5$, we can see that the test curve approaches Yunus correlation and tends to become a straight line, indicating that a fully developed free convection occurs when $Ra_\delta > 5\times10^5$. However, this phenomenon disagrees with Grigull and Haufs (1966) statement that a fully developed laminar convection regime occurs when $Ga_\delta > 3.0\times10^4$ (i.e. $Ra_\delta > 2.1\times10^4$ for air). Considering the effect of the radius of curvature, the study of Powe et al. (1969) concluded that the radius of curvature, though not affecting the general type of flow pattern, did affect the specific values of Grashof number at which transition from a steady to an unsteady flow occurred. They also pointed out that the decrease in radius of curvature resulted in an increase in the transition Grashof number and suggested that further studies be carried out to substantiate this effect. Note that the inner cylinder diameter Di we

[1] Named after the author's first name
[2] Named after the organisation initials.

investigated was 762 mm and the diameter ratios were small, in the range of 1.03< Do/Di < 1.3, comparing to the previous studies where 1.3 < Do/Di <6.3. This means that the radius of curvature in our model is smaller than that studied by Grigull and Hauf. Hence it can be expected that there exists a relatively higher transition Rayleigh number ($Ra_\delta = 5\times10^5$) at which heat transfer regime changes from a transition region to a fully developed laminar convection.

Thus, it is summarized that for a large diameter (Di = 762 mm) and small diameter ratio (1.03< Do/Di < 1.3) annulus, the heat transfer regimes for atmospheric-pressure air inside a concentric gap are identified as:

- ***Pseudo conductive regime***: $Ra_\delta < 2.3\times10^3$
- ***Transition regime***: $2.3\times10^3 < Ra_\delta < 5\times10^5$
- ***Fully developed convection :*** $Ra_\delta > 5\times10^5$

It is important to note that our design air-gap range (10 – 75 mm gaps) for the geothermal application is mostly in the transition region, which is not a straight line in the log-log plot in Fig.5. Hence the existing power law correlations are invalid for our design range. Although Kuehn & Goldstein's correlation considered the transition region, it depends on the Grigull and Haufs categorization of flow patterns, which do not match the heat transfer regimes being investigated by us. Hence, it is necessary to generate a new correlation for the design of air-gap insulation for large geothermal pipelines.

Note that, in Fig.5, both B&C and R&H correlations should have a minimum Nusselt number approaching unity for small Ra_δ ($Ra_\delta < 4\times10^3$ and $Ra_\delta < 1\times10^4$ respectively). This is due to the fact that the true heat transfer rate cannot be smaller than that of the pure conduction.

4. RECOMMENDED NEW CORRELATIONS

Since it is impossible to have a simple power law correlation to fit our test results, a set of correlations for the different heat transfer regions is required. A set of four correlations is recommended as shown in Fig.6.

By using the "Curve Fit" function in Engineering Equation Solver (EES) software, two new correlations are generated for the transition region. Also, Yunus correlation is recommended for the fully developed convection region. Because there is no test data for $Ra_\delta > 1.1\times10^6$, the extended straight line in this region indicates the curve trend only. In the pseudo-conduction region, the Nussult number is chosen as unity from heat transfer theory, and is indicated by the horizontal line.

It should be emphasized that the model we investigated had a characteristic that its outer cylinder (outer cladding) was not isothermal but convectively cooled, causing the upper part to be hotter than the bottom. So, the average surface temperature of the outer cylinder was used for calculations in each gap measurement data.

Thus, for large diameter (Di = 762 mm) and small diameter ratio (1.03< Do/Di < 1.3) annulus, with its outer cylinder convectively cooled, the correlations for the natural convection inside the air gap are recommended as follows:

Pseudo conduction region

$$Nu_\delta = 1\ ; \qquad Ra_\delta \le 2.3\times10^3 \tag{3}$$

Transition region

$$Nu_\delta = 0.23 Ra_\delta^{0.19}\ ; \qquad 2.3\times10^3 \le Ra_\delta \le 7.2\times10^4 \tag{4}$$

$$Nu_\delta = 0.0089 Ra_\delta^{0.49}\ ; \qquad 7.2\times10^4 \le Ra_\delta \le 3.1\times10^5 \tag{5}$$

Fully developed convection region *(Yunus correlation)*

$$Nu_\delta = 0.11 Ra_\delta^{0.29}\ ; \qquad Ra_\delta > 3.1\times10^5 \tag{6}$$

Equations (4)-(6) were used to recalculate the convective heat transfer rates and the results are plotted against air-gap size as shown in Fig.7.

As expected, the test data fit well with the new correlations in Fig.7. The maximum error occurs at 20 mm gap (3.6 %). From engineering point of view, this is considered accurate and acceptable for determining the optimum air gap as well as for the heat loss calculation. Hence equations (3)-(6) are recommended for the design of air-gap insulation of large diameter geothermal pipelines.

5. CONCLUSIONS

An experimental study of air-gap insulation for large geothermal pipelines had been carried out in the steamfield. By using the dimensional analysis, a categorization of heat transfer regimes for the geothermal application is identified and is considered important in theory. Furthermore, new correlations [Eq. (3)-(6)] are recommended for engineering design of single layer air-gap insulation.

ACKNOWLEDGEMENTS

The authors thank Contact Energy Ltd for their permission to use the Wairakei steam pipeline in this study. The direct assistance of Mr. Chris Morris, Production engineer, and Mr. Lew Bacon, Station Chemist, at the Wairakei Power Station is gratefully acknowledged.

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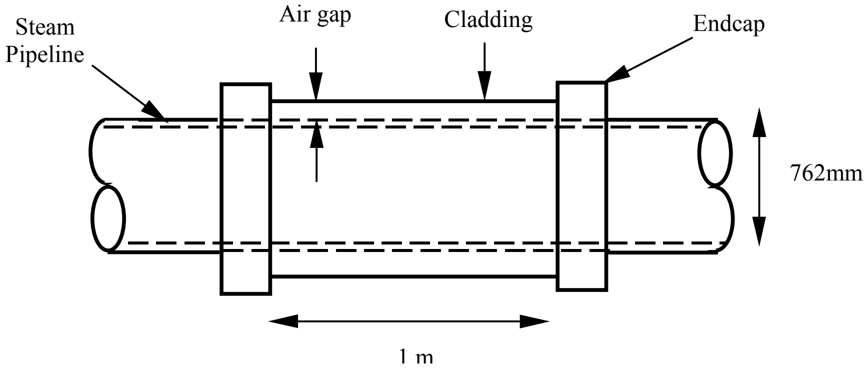

Fig.1: Schematic configuration of the pipeline and cladding

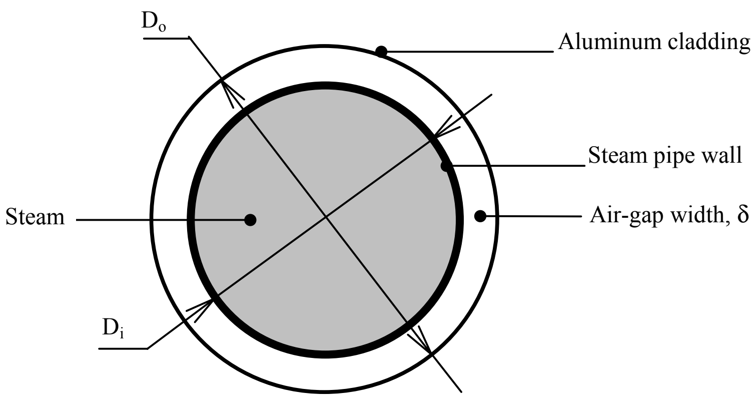

Fig. 2 Horizontal cylindrical steam pipe with a concentric air gap and aluminum cladding

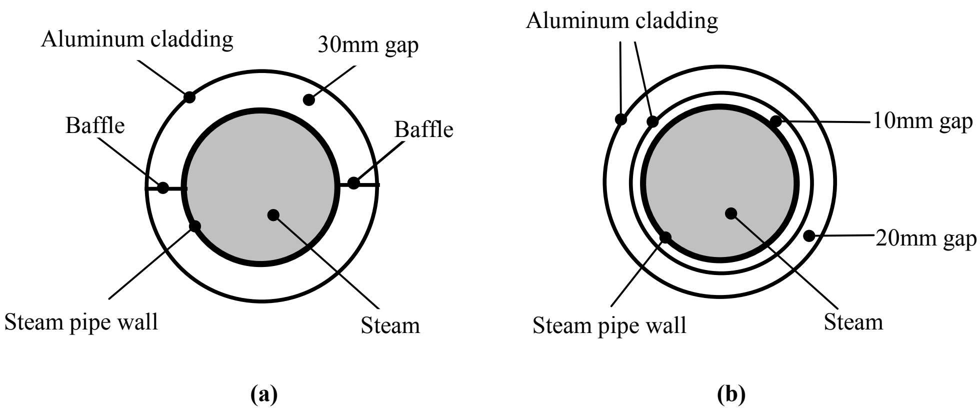

Fig. 3 (a) Horizontal coplanar baffles; (b) Double-layer configuration

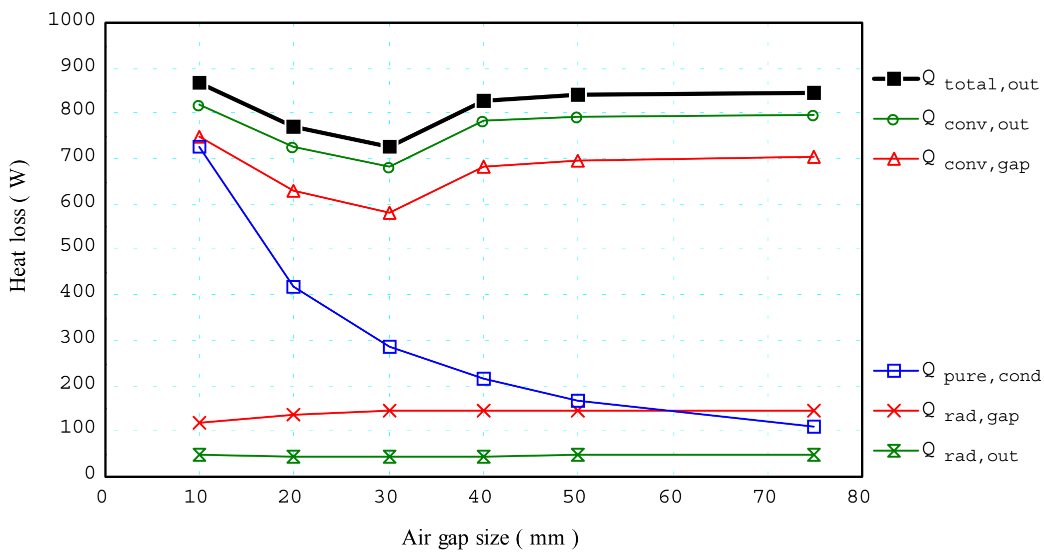

Fig.4 Heat loss across the air gap in terms of different modes of heat transfer

Table 1 Comparison of baffled and double-layer gap models to none baffle single layer air

Air Gap	Pipe surface temp. (°C)	Cladding temp. (°C)	Ambient temp. (°C)	Total heat loss (W)
Baffled gap	157	63	19	667
Double layer	150	47	16	429
Single layer	157	67	20	725

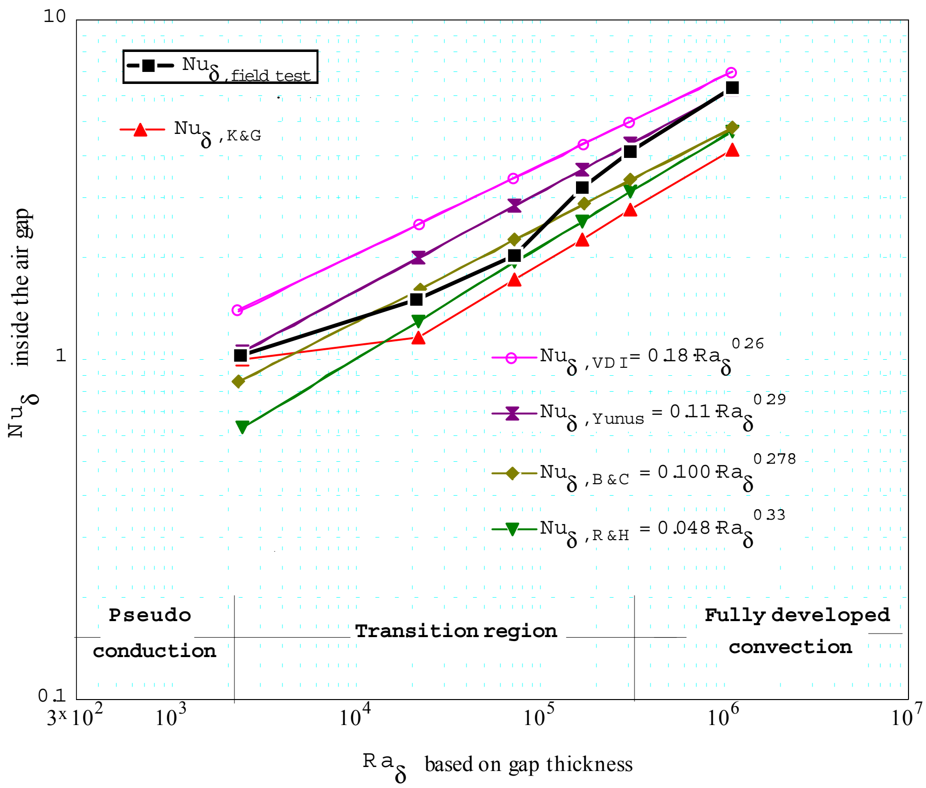

Fig.5 Dimensional analysis of the field tests and comparison with various correlations

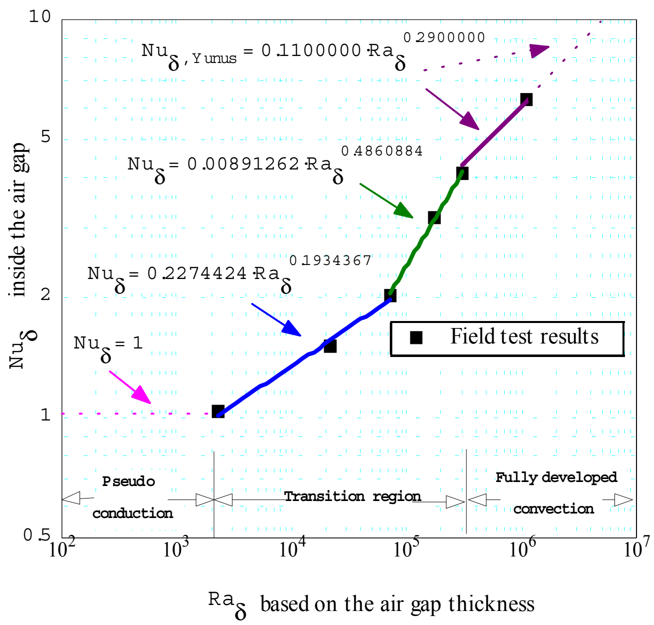

Fig.6 Recommended new correlations for different heat transfer regions

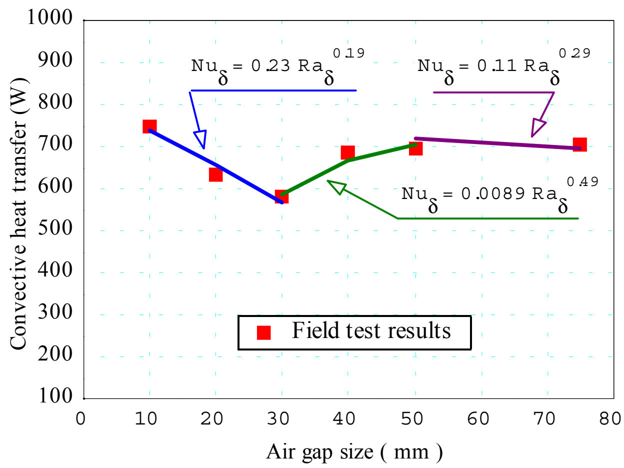

Fig.7 New correlations plotted on convective heat transfer inside air gap versus gap size