of Pr with respect to the use of Eq. (30) or (31), that is, the value of Pr for which $Pr = Pr_t$, is 0.867 according to Eq. (32). Other correlating equations for Pr_t give only slightly different numerical values for this pivotal value of Pr. Either Eq. (30) or Eq. (31) can be used without serious error for $0.45 < Pr < 1.7$, which suggests that Eq. (30) is a sufficient expression for all fluids other than liquid metals.

SUMMARY

Equations (30) and (31), together with Eq. (32), predict values of Nu within 1% or 2% of numerically calculated values for all geometries and conditions in the fully turbulent regime. This is to be compared with deviations of 10% to 40% on the mean for all expressions in current use, many of which are greatly restricted with respect to range and conditions (see Churchill and Zajic[3]). The remarkable improvement in accuracy for $Pr \geq Pr_t$, as provided by Eq. (27), is a consequence of using the Reichardt analogy, which is free of any explicit empiricism. This expression fails in exactness only due to some minor mathematical simplifications made in its derivation. This slight inaccuracy is in turn virtually eliminated by use of the analogy of Churchill. On the other hand, the greatly improved accuracy of Eq. (31) for $Pr \leq Pr_t$ is a consequence of the identification of the structure of the analogy of Reichardt with that of the generic correlating equation of Churchill and Usagi for three regimes in staggered form, together with a minor empiricism. This same identification revealed a virtual regime and a point of inflection for $Pr \leq Pr_t$, and another such pair that had never before been recognized for $Pr > Pr_t$. The existence of these virtual regimes explains the numerical and functional failures of most prior correlating equations.

The generality of the new expressions for all geometries and thermal boundary conditions is a consequence of the recognition that the analogy of Reichardt could be expressed in terms of Nu_0, Nu_1, Nu_∞, and Pr/Pr_t. The supplementary expressions for Nu_0, Nu_1, and Nu_∞, which are exact insofar as Pr_t is independent of y^+, follow directly from formulation of the equations of conservation in terms of the fraction of the transport due to the turbulent fluctuations. They could have been derived using eddy diffusional models, but not so simply.

Implementation of the new expressions for specified values of Re and Pr, and for particular geometries and thermal boundary conditions, is not onerous since the entire calculation can be preprogrammed.

The path of development leading to Eqs. (30) and (31) could now be streamlined, but the description of the irregular path that was actually followed has educational value in that all students and practicing engineers should be concerned with the evaluation if not the construction of correlating equations.

Although the process of derivation of the new relationships for thermal convection is much more complicated, and the relationships themselves are slightly more complicated to employ, these deficiencies appear to be a small price to pay for their greater accuracy, sounder rationale, and broader applicability.

Students should be prompted to question any of the assertions and non-obvious steps that were made in the abbreviated development herein and not expanded upon by the teacher. Justifications may generally be found in the references.

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ChE letter to the editor

Dear Editor:

Late last year, you published our Letter to the Editor regarding a survey we were carrying out on the use of Inherently Safer Design (ISD), meant to make the process industry a lot safer. Several of your readers downloaded our questionnaire and sent their responses to us. We got responses from eleven countries world wide.

The findings of the survey have just been published under the title "Inherently Safer Design: Present and Future" in the *Transactions of the Institution of Chemical Engineers, Process Safety and Environmental Progress,* **80**, Part B, May 2002.

We are pleased to enclose a copy of the publication for your reference. Further, the following is a brief summary of the survey paper. It's appearance would be a fitting finale to the effort that started with the initial publication of our letter in your journal.

Summary

A recent survey of the current use of Inherently Safer Design (ISD) concepts attracted responses from 63 people in 11 countries. These included industrialists, consultants, regulators, and academics. The salient results of the survey are noted below in bullet form to focus attention, followed by recommendations to expedite the adoption and spread of ISD.

- Almost everyone responding knows of ISD. Their knowledge stems from specialized lectures, short courses, books, conferences, and training videos.
- ISD has been practiced by some for decades, whereas others started only recently.
- ISD is used in almost all stages of chemical process development, design, and operation.
- ISD is used during the manufacture of a whole range of products.
- Almost all hazards have been targeted, both on-shore and off-shore.
- The above attests to the universality of ISD applications.
- There is a favorable impact on balance sheets.
- It is important to use "Management of Change" when implementing ISD to avoid introducing any new hazards.
- There is very little additional cost if implemented early. Payback is fast.
- Some applications/practitioners have won awards.
- ISD is included in lectures at several institutions. More will do so now.
- Many are not familiar with the current Inherent Safety (IS) indices. Those familiar with them have used them sparingly. A simple, realistic index is needed that also shows economic benefits. Detailed examples of use at different stages of process development are necessary.
- ISD concepts can influence R&D in various areas of chemical engineering and chemistry.
- ISD should encompass inherent safety, health, and environment (ISHE).
- ISD concepts, suitably modified, can be used for other branches of engineering such as mining, construction, transport, etc.
- Current regulations do not force the use of ISD.

Recommendations

The sad truth is that ISD is applied when an ISD enthusiast is on the team and not otherwise. Implementation of the recommendations below might encourage the uptake of ISD.

- Every chemist and chemical engineer should be trained in ISD. Academics and professional bodies should lead in this.
- Other scientists and engineers should be given introductory lectures in ISD with examples from different industries.
- IChemE should make ISD a part of its approved degree syllabus. Subsequently, it should persuade other engineering and science accrediting societies to do likewise.
- There is a need to teach IS to management and financial people also since their role is crucial in encouraging applications of ISD.
- Dedicated funding by government and industry for research and teaching in ISD will encourage many academics to take it up.
- Incentives by the government to cost share demonstration plants and provide tax breaks for ISD.
- Expand ISD to encompass ISHE since the environment and occupational health are day-to-day concerns. It may eventually be extended to ISHEQ (Q for Quality) since improvements in SHE will decisively impact quality of product.
- Companies should provide examples of ISD use in various situations and the economic benefits reaped in order to convince other industries, regulators, government, the media, the public, academics, R&D funding agencies, etc.
- Involve the mainstream print and audiovisual media to favorably impact public opinion.
- Amend regulations to enforce the use of ISD.
- Insistence by international agencies to include ISD in projects that they fund in the same way that the World Bank now insists on environmental impact assessment studies in projects funded by it.

Some expected results

- Tall columns of chemical plants will be reduced to one- or two-story heights. This will improve the image of the chemical industry.
- Increased investment in process industry.
- Less restrictive regulations.
- Greater enrolments in UG and PG courses.
- Significantly enhanced funding for R&D.
- Adoption of ISD by other engineering disciplines, especially the more accident-prone ones such as construction, mining, transportation, etc.

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