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Verification methodology for gas quality tracking systems for fiscal metering

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VERIFICATION METHODOLOGY FOR GAS QUALITY TRACKING SYSTEMS FOR FISCAL METERING

A gas quality tracking (GQT) system can be a cost-efficient solution for fiscal metering, if an update is needed to be able to cope with increasing gas quality variations. As part of the fiscal metering process, the accuracy of a GQT system has to be verified periodically to determine if accuracy requirements are met. In this paper a verification method for GQT systems for fiscal metering is presented. The scope of the verification methodology is regional gas grids with multiple entries.

Introduction

At fiscal metering system connections where gas is being transferred from one party to another, the delivered amount of energy is determined. Because of the importance of correct billing, the measurement of transferred energy should be secured in the fiscal metering process. The performance of this process should be continuously monitored and periodically evaluated.

Nowadays the gas supply diversifies towards (new) supplies with varying gas qualities, e.g. new transit lines or de-central feed-in connections for green gasses. Traditionally gas networks were supplied with a rather constant gas quality, which required a relatively simple fiscal metering system in order to meet accuracy requirements. The trend in diversification of the supplies will cause a more varying gas quality in the network. Due to these changes, calorific value variations up to 10% could be expected, while fiscal metering requires an uncertainty on delivered energy smaller than e.g. 1%. Consequently, changes in the fiscal metering process should be adopted to be able to handle the increasing variations in gas qualities, while it continuously meets the requirements.

For small industrial or city gate stations it is best practise to measure gas quality with a Gas Chromatograph (GC) installed upstream of multiple stations. However, in this process setup one has to take into account the additional uncertainty on delivered energy that originates from transport or residence time of gas in the distribution network.

A GQT system tracks the propagation of gas quality variations through the distribution grid by means of hydraulic network simulations. With a GQT system variations in gas quality are more accurately allocated to multiple downstream stations in comparison with simple algorithms, e.g. a moving average. Therefore, the GQT system allows for a more varying gas quality in the network, while compliance with requirements stays secured. Moreover, to adapt the fiscal metering process for increasing variations in gas quality, the implementation of a GQT system as a fiscal metering application provides a cost-efficient solution compared to the installation of GCs at all gas delivery points.

Requirements, whether determined by regulation, or contractual agreements should be considered carefully before implementing a GQT system. Furthermore, specific system aspects should be taken into account for different parts of the system, e.g. the simulation program, fiscal and non-fiscal data and network topology description. To secure the quality of a GQT system as part of the fiscal metering process the accuracy and applicability of the system for regional networks should be verified and periodically evaluated.

Requirements

The acceptable uncertainty of a GQT system depends on regulatory or contractual requirements. For small industrial or city gate gas stations the uncertainty on delivered energy is typically ≤2% on an hourly basis.

The measurement of transferred energy in regional grids basically consists of three elements:

- Transferred gas volumes – Q [m^3(n)/hr]
  Measured at fiscal metering points
- Gas quality – H_s [MJ/m^3]

Measured at upstream GC location

- (Correction for) transport time – RT [hr]
  E.g. a GQT system or a simple algorithm

The uncertainty in Q is typically ≤1% and in H_s ≤0.5%. Both Q and H_s are measured independently and these measurements are normally distributed. It then follows from the square root of the sum of squares that the part of the ≤2% uncertainty 'budget' on energy that is left is:

$$1.65 = \sqrt{2^2 - 1^2 - 0.5^2}$$

The additional allowed error in H_s at gas delivery points is ≤1.65%. This uncertainty is a critical requirement for a GQT system.

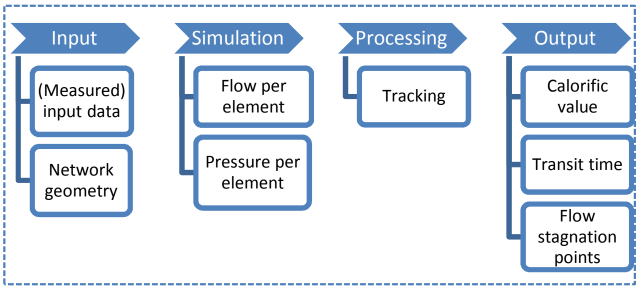
Now, a distinction is made between variations in H_s supply smaller and larger than 1.65%. In the first case the GQT system automatically meets the ≤1.65% requirement, because then the calculated H_s value will always be within 1.65% of the actual H_s value at offtake locations. In the second case, when H_s variations >1.65% are introduced in the distribution grid, for example as a step change, the deviation between actual and simulated H_s value at offtakes may also be >1.65% for a period of time. This time period is equal to the deviation between the real transport time and the time as calculated with a GQT system. For this duration the calculated H_s value(s) is not reliable enough for fiscal purposes.

The deviation between real and calculated transport time is network specific. The aim of the presented verification methodology for GQT systems in fiscal metering is to verify the maximum time deviation between calculated and real transport time for regional networks.

GQT system overview

The core of a GQT system is a hydraulic network simulation program. Such a program utilizes (measured) input data and network topology data to perform real time dynamic simulations of the gas transport network. The time step of the simulation is equal to the resolution of the input data time series, e.g. one hour. The simulation program calculates the flow and pressure per piping element, which is then used to track gas quality 'fronts' through the gas grid. The final result of a GQT system is a calculated H_s at all exit points of the gas distribution grid. Furthermore, other parameters like the transport time and the location of flow stagnation points can be assessed by processing the simulated flow and pressure data.

Figure 1: GQT system overview



Considerations

In the development of the methodology several considerations have been taken into account, which influence the feasibility of the system.

Uncertainty of simulation input parameters:
The input data for a GQT system consists of measurements and best estimates. The first category consists of for example flow and pressure input data. The measuring instruments should be calibrated. For the second category, consisting of e.g. gas temperature and wall roughness input data, best estimates are used. These estimates can be based on for example historical data.

For both categories the uncertainty interval and distribution of each individual input parameter should be provided.

Time step of input data:
The time step of input data time series, for example one hour, is another constraint for the GQT system accuracy. Although the variations in the value of the input data within a time step interval might be small, the actual variations are unknown. This yields for the time step interval before and after an input data point. Therefore, the minimum uncertainty in transport time is at least two times the time step interval.

The time step of the simulation program is typically set equal to the input.

Flow variations at exit points:
Variations in flow at exit points can be large and depend on the behaviour of the end customer(s), e.g. residential or industrial. Because gas supplies to the low pressure, residential market have a strong correlation with the ambient temperature, the gas flow profile of these exit points varies per during the year. The gas flow through these exit points can be high during winter and low or even zero in summer. The gas supply to industries is less, or not, related to temperature. However, dependent on the type of industry the demand profiles could alternate between high and low or also even zero flow.

Single and multiple entry networks:
Regarding the network geometry, a distinction is made between single entry and multiple entry networks. In the case of a multiple entry network, delivery stations can receive gas from more than one supply, depending on the network state – i.e. flow and pressure conditions in the network. This can be a mixture of the gas from several entries, or switching between single entries, due to a moving stagnation point. At these delivery stations, variations in H_s originate from variations in the gas composition at entry points from which it receives gas, as well as on the mixing ratio of the gas streams from the different supply points.

In networks with more than one entry, both transport time and mixing factor are very sensitive to small pressure variations at entry points. Small pressure variations strongly influence the position of the locations in the network where two or more gas flows from different supply points mix. A small change in pressure at an entry could shift the location of this so-called stagnation point significantly, causing a switch in the supply source for a customer. Even small deviations in the order of magnitude of a pressure sensor uncertainty interval can have a significant effect on the network state.

Dynamic transport time:
Mainly due to variations in flow at exit points and the sensitivity for small pressure variations in multiple entry networks, transport times vary. The effect of typical temperature and quality parameter variations on transport time are small.

Calculated H_s characteristics:
The calculated H_s at gas delivery points can deviate significantly from H_s measured with a GC upstream. H_s at offtakes will change not only dynamically shifted in time, but also in H_s value. Multiple routes may exist in a gas distribution network and gas may blend at mixing points. This could mean that gas from different supplies could blend, but also gas with different time stamps from a single entry, as the transport time along different routes differs. These network geometry related factors result in H_s dampening.

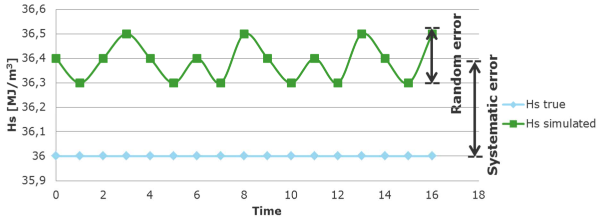
Origin of deviations:
A GQT system utilizes real measurement data and network geometry data to calculate the calorific value at a gas delivery point, taking into account transport time. Deviations will occur between real and calculated values at gas delivery points. These deviations originate from sources of uncertainty or biases in the calculation. The deviations can be classified in three types:

1. Deviations due to uncertainty in measured input data: These inputs are for example a gas flow at gas delivery points, a pressure at network entries and the calorific value. These measurements have uncertainty. In case the actual measurement uncertainty of an input parameter is unknown, one can choose to use a best estimate (worst case approach).
2. Deviations due to biases in network geometry: The modelled network can differ from the real network in length, diameter, wall roughness, elevation, valve positions, etc.
3. Deviations due to biases in gas flow modelling: In modelling the gas flow in a network, simplified thermodynamic and flow equations are applied to handle the high number of necessary calculations in an efficient way. For example, the assumption that small pipeline elevation is negligible.

Random and systematic errors:

In the analysis of deviations between real and simulated H_s values at exit points, two error categories are distinguished: random and systematic errors. In Figure 2 the difference between random and systematic errors is shown graphically.

Figure 2: The difference between random and systematic errors



Verification methodology for a GQT system

Before a GQT system can be used in the fiscal metering process, a sequence of verification steps has to be completed. This procedure is meant to check and validate whether the requirements are met for a particular distribution network. Furthermore, the procedure should take into account all the different aspects as described above. The procedure consists of three main phases:

1. *A study phase* in which a pre-analysis of the entire distribution network under consideration will be performed:
   a. to determine the effect of random uncertainties in input data on the resulting random deviations in the calculated transport time, and
   b. to identify the location of control GC's to verify the results of a GQT system in the case random deviations are too large.

2. *An implementation phase* which will consist of the installation of control GC's at the locations determined in the study phase and in parallel field verification measurements to check for systematic errors in the network topology

3. *An operational phase* in which the configuration of the GQT system will be periodically validated and evaluated.

In Figure 3 an overview of the verification plan is given. In the following sections a detailed explanation of each phase is provided.

Study phase

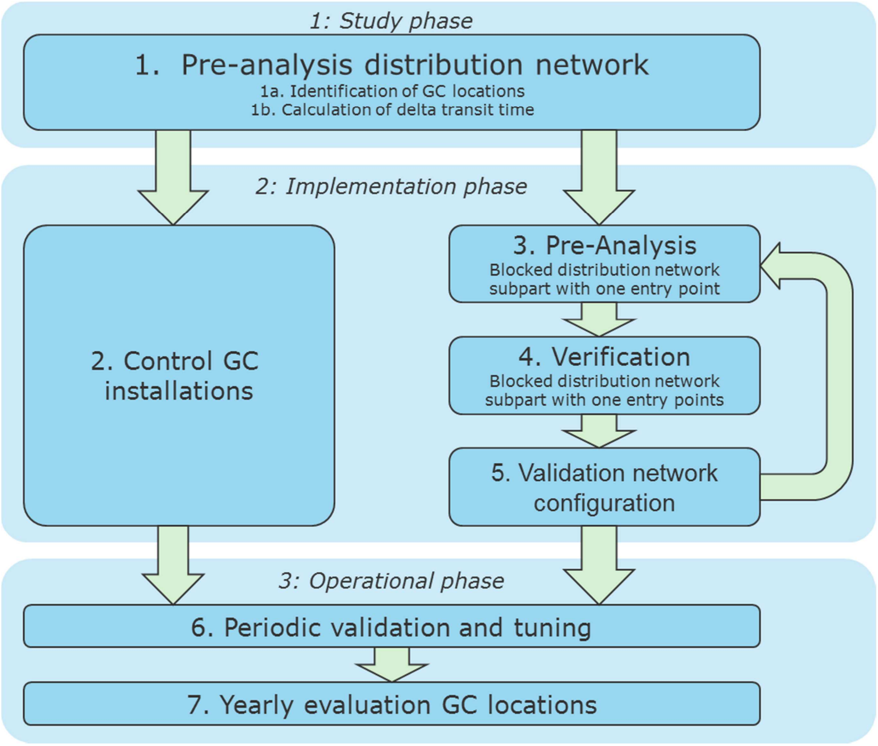
In the study phase the magnitude of random deviations in transport time, ΔRT, is calculated for a specific distribution grid. These random deviations originate from uncertainties in the simulation input data and in the network geometry. Because (uncertainties in) input data and network geometry are a given, the calculations provide an estimate of the minimum uncertainty in transport time, i.e. the smallest obtainable random error bandwidth without any systematic errors.

For complex networks, e.g. larger networks or networks with multiple supplies, ΔRT could be large. In that case control GCs are placed at tactical locations in the network to be able to meet the requirements. These GC's are used to check the results of the GQT system. Their locations are determined in the study phase as well.

ΔRT and the locations of control GCs are derived from running a number of Monte Carlo trials, where input data are varied within their specific uncertainty ranges. Representativeness of input data is taken into account to ensure that the outputs of the simulations reflect expected gas flows for the future.

When the study phase results show that the GQT system is fit for purpose for the network under consideration, the implementation phase of the program is started. In case of a negative result the grid area covered by the GQT system needs to be redefined, i.e. subdivided into smaller grid areas.

Figure 3: Verification plan overview



Input data representativeness:

A number of aspects have to be taken into account regarding input data representativeness, e.g. the dependence on pressure and flow data, the incorporation of expected future pressure and flow conditions, distribution of input data uncertainty, propagation of uncertainty, customers with zero flow for specific time periods, and multiple routes per offtake in a regional network.

The problem is to define a dataset which is representative for the future and for all possible transport situations that occur during a normal year. Up till today a selection of input data from the previous year has been used in the study phase. However, not all aspects mentioned above have been taken into account in these selections. By evaluating on a yearly basis study phase results could be updated if required. In parallel, research is carried out to find a practical selection method for simulation input data that covers all aspects.

Simulations:

The propagation of uncertainties from input parameters on transport time can be studied with a Monte Carlo method [1]. A number of network simulations are carried out with randomly selected variations on the original data. These random variations of the original data are chosen within the measurement uncertainty of the given input parameter. The calculated transport times for each simulation are compared with the reference case to obtain the error distribution in calculated transport time at exit points.

The computational effort to perform a full Monte Carlo analysis is very large. A value of $M = 10^6$, where M is the number of Monte Carlo trials, can often be expected to deliver a 95% coverage interval for the output quantity such that the results are correct to one or two significant decimal digits [1, §7.2.1]. For this application it is practical not feasible to use a large value of M.

In this case in literature other approaches are suggested:

1. A relatively small value of M, e.g. 10 or 50: Although this use of a small value of M is inevitably less reliable than that of a large value, it does take account of model non-linearity [1, §7.2].
2. A value of M = 1600: Here the assumption is that the variances of the Monte Carlo results are converging. Furthermore, the value of M is calculated utilizing the quantile of the normal distribution. To obtain a relative accuracy for the uncertainty of 5% with a probability of 95% this results in a number of 1600 simulations [2].

Based on two considerations, it is chosen to run a relatively low number of 10-50 simulations. The first argument is that a value of M = 1600 still would be demanding a significant computational effort. The second consideration relates to the balance between the reliability of calculated ΔRT and input data representativeness. The reliability of the calculated ΔRT not only depends on the number of simulations, but is also highly affected by input data representativeness. Input data representativeness is not expressed in terms of 95% probability and it is expected to be less reliable.

Delta transport time:
The magnitude of the random variation (deviation) in transport time, ΔRT, is used as the main parameter that is evaluated to determine if a GQT system complies with the governing metering requirements. Furthermore, the largest observed ΔRT at a gas delivery point is applied to all other offtakes as well.

These two choices have been made while taking into account the following considerations:

1. The error in calculated H_s at gas delivery points is dependent on how rapidly H_s changes in time at the entry point. However, the effect of variations in H_s on the calculated transport time is negligible. Therefore, calculating ΔRT eliminates the effect of H_s profile characteristics which are often difficult to forecast in expected future situations. The final translation to metering requirements taking into account expected variations in H_s can then be done afterwards.
2. The second argument is that by applying the largest observed ΔRT to all offtakes a worst case approach results and furthermore this limits the number of simulations required.

Control GC's:
In networks with more than one entry, both transport time and mixing factor are very sensitive for small pressure variations at entry points. Calculating both transport time and mixing factor accurately for delivery stations that receive gas from more than one entry results in non-feasible accuracy requirements for input data parameters. Therefore, it is chosen to place control GCs at tactical locations in the distribution grid to be able to meet the GQT system requirements.

The advantage of installing control GCs is two-fold. Firstly, H_s is essential for determining energy quantities. If a control GC is installed at a gas delivery station the determination of H_s for this station is based on the actual GC values. Therefore, the determined energy for this offtake will fulfil metering requirements. Secondly, H_s carries 'information' about upstream gas quality variations that originates from variations at entry points and from the network configuration, for example the location of a mixing point. If a control GC is installed at an offtake receiving gas from a single entry, then it only contains information about the propagation of gas between these two points. When a control GC is placed at a delivery station receiving gas from more than one entry point, then it contains information about gas quality variations at these entries and the mixing ratio of the gas streams.

In case the difference in H_s between entry points and the mixing factor are both sufficiently large to be detected by a control GC, the gas quality measurement can be used to validate the simulation. When the H_s calculated by the GQT system matches H_s as measured with the control GC this provides validation of:

- A correct simulation of the location of stagnation points. If the locations of stagnation points are known, then this also means that the entries from which each offtake receive gas are simulated properly.
- Furthermore, an accurate simulation of the mixing factor means that all transport times have also been calculated correctly.

Based on the position of stagnation points and mixing point areas determined in the study phase, in general control GCs are installed at offtakes located in these areas.

Implementation phase

Next to the study phase four steps are identified in the implementation phase. The implementation phase consists of the installation of control GC's at the locations determined in the study phase and a 3 step verification plan to check for potential systematic errors in the network topology. The installation of control GC's can be executed in parallel with the network topology validation.

The propagation of uncertainty through networks with a single entry will be small compared to networks with multiple entries. For the purpose of network topology verification, the distribution network is therefore divided in subparts with one entry point. In the same way as described previously, Monte Carlo trials are run to determine ΔRT for these subparts.

At selected exit points in the subparts of the distribution network direct calorific value measurements with portable micro GC's are executed. By comparing the network simulations with the results of the field measurements (for the same period) it can be determined if the network topology of the subparts is modeled correctly. If this is the case, observed differences between simulated and measured transport times should be within ΔRT, see figure 4a and 4b.

Figure 4a: Validation principle of modelled network geometry: deviations between simulated and measured RT should be within ΔRT.

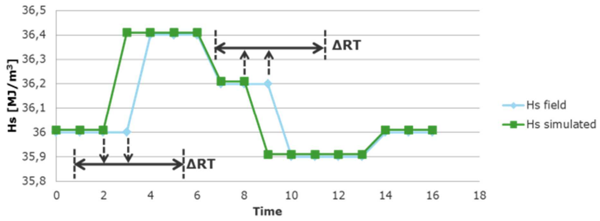
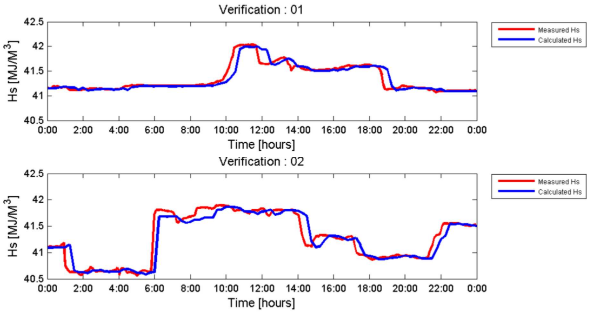


Figure 4b: Validation results of a regional distribution network



If the observed differences between simulated and measured transport time are larger than ΔRT the modeled network topology (e.g. pipe length, diameter, wall roughness) should be validated.

Operational phase

When the GQT system is operational for the entire distribution network, periodic validation and tuning can be performed to align simulation results with control GC measurements. Finally, a yearly evaluation of GC locations is foreseen to incorporate future changes in e.g. variations in calorific value and (dynamic) offtake profiles.

Periodic validation and tuning:
With the aim to let the simulation results correspond with measurement values of installed control GCs in the distribution network, periodic validation and (if necessary) tuning of the inlet pressure at entry points (in the simulation tool) could be done.

The tuning procedure has not been developed yet. Up till now tests have been carried out by manually changing inlet pressure data within their uncertainty intervals. The results look very promising and provide a basis for future research.

It is anticipated that there are basically two approaches to cope with tuning. The first approach is manually adjusting the simulation input data. The second approach is automatically calculating the adjustments in input data by means of a state estimator. A state estimator can determine a solution that fits with the control GCs measurement data by adjusting input data within their specific uncertainty intervals. Moreover, it provides functionality to check if all input data are still reliable.

Yearly evaluation control GC locations:
By repeating the study phase with the latest historical data and supply/demand forecasts available, the current control GC locations may be checked and if necessary reconsidered.

Discussion and conclusion

The proposed verification plan has been developed and applied to an operational GQT system in the fiscal metering process of the Dutch gas transmission system operator. In 2007-2009 a methodology was developed for regional networks with a single entry and later this was expanded to multiply entries distribution networks. The first regional grid with a single entry for which the billing process included calculated H_s with a GQT system was operational in 2009. Since then more than 10 regional grids have been verified according the described methodology. The experience is positive and results provide the evidence that an implementation of a GQT system in the fiscal metering process is feasible and meets requirements.

The presented GQT system overview distinguishes four blocks – i.e. input, simulation, processing and output. Because a typical simulation program does not provide functionality to determine transport routes or to calculate transport time these modules have been developed separately. This 'processing' is only necessary for the verification and not during normal operation of a GQT system. The modules are not described in detail in this paper.

Two aspects have been identified, i.e. input data representativeness and periodic validation and tuning that should be further studied. Although already a large number of aspects are covered within the methodology, these two aspects may involve additional uncertainty that needs to be taken into account.

Scientific justification:
It is chosen to provide in this paper a high level description of the verification plan rather than a detailed 'case' analysis. However, because the methodology has been applied in practise the presented methodology is supported with well documented case analyses. The results included in this paper are used for clarification. For the purpose of this paper these results have been anonymized to avoid any conflict of interests. All data is stored and therefore reproducibility of results is secured.

About the author

Martijn Douwes works at DNV GL in the field of gas transmission network simulations. From the first feasibility studies onwards Martijn has been involved in the development of the verification plan and he currently participates in research projects dedicated to improve GQT systems. Martijn holds a Master degree in Fluid Dynamics in Mechanical Engineering.

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/1/ Guide to the Expression of Uncertainty in Measurement Supplement 1: Propagation of distributions using a Monte Carlo method, JCGM 101:2008

/2/ Uncertainty evaluation for quality tracking in natural gas grids, R. Kessel and K.D. Sommer, 2013

List of definitions

GQT system	A Gas Quality Tracking system calculates transport times, i.e. residence times of gas from entry to exit point in a particular part of a gas transport network. The purpose of the transport time calculation is to simulate the calorific value at the exit points based on the of calorific value measurement(s) at the entry point(s).
Network topology	Complete description of a part of the transportation network, consisting of piping elements connected by nodes.
Transport time	Transport time is the dynamic residence time of natural gas between entry and exit point in a particular part of the transportation network.
Delta transport time	Deviations in calculated transport time due to (measurement) uncertainties in simulation input data.
Route	A particular set of piping elements connecting the entry and the exit point. In complex networks multiple routes can exist between entry point(s) and exit point.
Stagnation point	Location in the network, in a pipe segment or at a T-junction, where two gas streams from different directions mix.
Mixing point area	Due to for example dynamic off take profiles, the position of the stagnation point is variable. The area in the distribution network in which the stagnation point location ‘travels’ is called the mixing point area.
Control GC	A GC installed at a location in the distribution network to be able to continuously validate and tune the GQT system.

List of abbreviations

GC	Gas chromatograph
GQT	Gas quality tracking

List of symbols

Q	Flow at exit points [m^3(n)/h]
P	Pressure at entry points [bar(g)]
H_s	Superior calorific value [MJ/m^3]
RT	Transport time [hr]
ΔRT	Delta transport time [hr]
M	Number of Monte Carlo trials [-]

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